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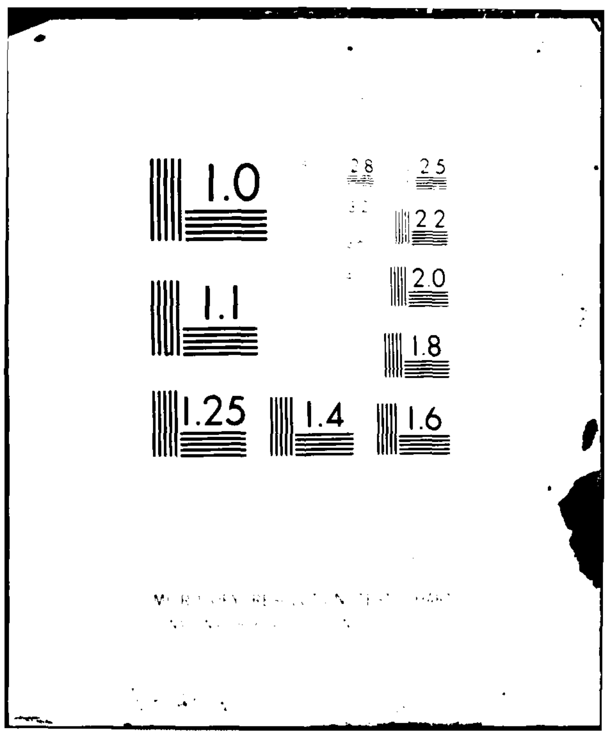
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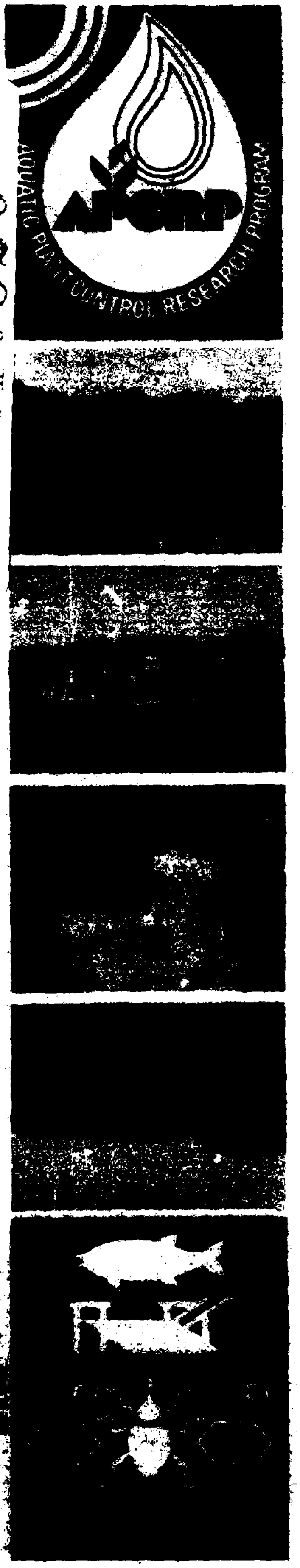

TECHNICAL REPORT A-81-6

EVALUATION OF THE MODEL CE-QUAL-R1 FOR USE BY THE AQUATIC PLANT CONTROL RESEARCH PROGRAM

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Final Report

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The Corps of Engineers One-Dimensional Reservoir Water Quality Model (CE-QUAL-R1) was evaluated for use in the Aquatic Plant Control Research Program (APCRP). This was accomplished by applying the model to a set of data collected at Lake Conway, Florida.

Calibration of the thermal portion of the model for a period of one year and subsequent verification for a period of three years produced satisfactory

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results concerning the water budget and temperature predictions. Calibration of the water quality portion of the model also produced satisfactory results. Measured data were not considered satisfactory for model verification.

It was concluded that CE-QUAL-R1 would be useful to the APCRP for predicting water quality variables after the addition of a macrophyte algorithm and after improvements are made concerning the interaction between the algorithms, time step, and solution scheme. All current model developments within the Environmental Water Quality Operational Studies Program should enhance model use for the APCRP. Other possible improvements which should be considered include the incorporation of: (a) output dealing with system function, (b) input via rainfall, and (c) effects of wind on sediments.

PREFACE

This study was conducted by the Water Quality Modeling Group (WQMG) of the Environmental Laboratory (EL), U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., for the Aquatic Plant Control Research Program under the work unit entitled "Predictive Techniques for Evaluating Aquatic Plant Control Strategies."

This report describes an evaluation of the Corps of Engineers One-Dimensional Reservoir Water Quality Model (CE-QUAL-R1) for use by the WES Aquatic Plant Control Research Program (APCRP). Principal investigator for the evaluation was Dr. J. H. Wlosinski, WQMG. Dr. E. C. Blancher, WQMG, prepared much of the data in a form suitable for modeling. Drs. D. E. Ford and K. W. Thornton reviewed the draft report. The study was conducted under the direct supervision of Mr. J. Norton, Acting Chief, and Mr. D. L. Robey, Chief, WQMG, and under the general supervision of Mr. D. L. Robey, Acting Chief, and Dr. R. L. Eley, Chief, Ecosystem Research and Simulation Division, EL, and Dr. John Harrison, Chief, EL. Mr. J. L. Decell is Manager of the APCRP at WES.

Commander and Director of the WES during the conduct of this study was COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

EVALUATION OF THE MODEL CE-QUAL-R1 FOR USE BY THE AQUATIC PLANT CONTROL RESEARCH PROGRAM

PART I: INTRODUCTION

1. The use of control methods for managing nuisance aquatic plants can have effects on components within the ecosystem that are not directly targeted for control. Since the possibility exists that the environmental quality of the resulting ecosystem may be less desirable than that existing prior to aquatic plant control, techniques are needed that will be able to predict the effects of control practices on the total aquatic ecosystem. These techniques are required to evaluate control methods that are being developed by the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., Aquatic Plant Control Research Program (APCRP).

2. One of the control methods currently being evaluated by the APCRP is the use of the white amur fish (Ctenopharyngodon idella). The white amur was introduced into Lake Conway, Florida, in the fall of 1977. For a year before the introduction, and for every year since, water quality data have been collected in an effort to monitor the changes occurring within the ecosystem.

3. Concurrently, but apart from the APCRP, the Water Quality Modeling Group (WQMG) of the WES Environmental Laboratory has been developing an ecosystem model (CE-QUAL-R1) of reservoirs. This model is being developed through efforts within the WES Environmental and Water Quality Operational Studies (EWQOS) Program. The model has been applied to reservoir preimpoundment studies in an effort to aid in the prediction of possible water quality problems and to study the effects of reservoir operations on water quality.

4. Because CE-QUAL-R1 contains many features that would be necessary to simulate lake ecosystems, the possibility exists that predictive methods for reservoir water quality problems will also apply to lakes. With this in mind, and to avoid duplication of effort, the objective of this study was to evaluate the CE-QUAL-R1 model for use by the APCRP. This was done by applying the model using the data collected at Lake Conway.

PART II: BACKGROUND INFORMATION

The CE-QUAL-R1 Model

5. The CE-QUAL-R1 model is a one-dimensional (horizontally averaged) mathematical model that represents the vertical distribution, in a lake or reservoir, of the following variables: thermal energy, shortwave radiation, dissolved oxygen, two algal assemblages, zooplankton, benthos, coliform bacteria, ammonium-N, nitrate-N, nitrite-N, orthophosphate-P, detritus, sediment, alkalinity, total dissolved solids, dissolved oxygen residual, daily oxygen demand, pH, and carbon dioxide-C. Three fish compartments are also included in the model, although their vertical distribution is not predicted. Model input includes initial estimates for all model components, coefficients for the equations of the model, and information concerning driving variables. Output consists of vertical profiles and downstream release values of the water quality variables and can be represented in tabular or graphical form.

6. The version of the CE-QUAL-R1 model used in this study was basically the same as used for an evaluation of water quality for a proposed reservoir (Ford et al. 1979). Additions to that model included computer code that allowed for the tracking of interactions between modeled variables, for testing the validity of the mass balance assumption, and for obtaining graphical output. In addition, the coefficient for sediment and detritus decay was separated into two coefficients that allowed for individual decay rates for the two compartments.

7. Application of the model for other studies performed by the WQMG has shown that temperature is an important factor for most of the variables included in the model. For ease in calibrating the model, subroutines dealing with temperature and the water budget were separated from water quality subroutines, thus creating a thermal model. This study followed the example of the other studies within the WQMG--that of calibrating the thermal portion of the model before attempting the calibration of the entire CE-QUAL-R1 model.

The Lake Conway Study Site

8. The Lake Conway System is comprised of a set of five interconnected pools located just south of Orlando, Fla. The pools are Lake Gatlin, the West and East pools of Little Lake Conway, and Middle and South pools of Lake Conway (Figure 1). Although data were collected at all five pools, only the Middle pool was modeled. The Middle pool has an area of 2.99 km^2 and a volume of 17.9×10^6 m^3. The average depth of the pool is 6.0 m, with a maximum depth of 12 m. Residence time is approximately three years. Further information concerning the Lake Conway study site can be found in reports by Theriot (1977), Nall and Schardt (1978), Guillory (1979), Conley et al. (1979), and Blancher and Fellows (1979).

PART III: DATA REQUIREMENTS AND SOURCES

9. Three categories of data are required by the CE-QUAL-R1 model: initial conditions, model coefficients, and updates. Initial conditions are the concentrations observed in the lake for the components included in the model. Ideally, initial conditions should be measured on the day the simulation is initiated at about metre intervals for the entire lake depth. Coefficients refer to the constants in the equations of the model. Updates for CE-QUAL-R1 include meteorological data and information concerning upstream flow.

10. The main sources of data for this study were collected, under contract, by the Orange County Pollution Control Department (OCPCD), the University of Florida Department of Environmental Engineering (UFDEE), and the Florida Game and Fresh Water Fish Commission (FGFFC). Extensive data for 1978 were taken from a study by Comp (1979). It must be realized that the Lake Conway Large-Scale Operations Management Test (LSOMT) for the study of the effects of the white amur did not have the application of CE-QUAL-R1 as one of its objectives. Therefore, the data may not be suitable for model evaluation.

Initial Conditions

11. The OCPCD collected the majority of data needed for initial conditions. Unfortunately, they usually only sampled from the surface to a depth of 4 or 5 m. Because the lake thermally stratifies in the summer (Conley et al. 1979) and because temperature affects the rate of change for most of the variables of the model, additional temperature data were needed in deeper strata for calibration purposes.

12. Additional temperature data for a one-year period were available from an independent study (Comp 1979) of the Middle pool of Lake Conway. The data were collected monthly at 1-m intervals from the surface to a depth of 9 m, and included data showing summer stratification. The simulations were started on 18 December 1977, coinciding with the first day of Comp's study. The remainder of Comp's temperature data was

used to calibrate the thermal portion of the model. After the model was calibrated, a verification simulation using data from OCPCD was made. The verification simulation started on 26 January 1976 and was run for a 34-month period. Since data from Comp (1979) showed that the lake was isothermal in January of 1978, the assumption was made that the temperature in the deeper unmeasured section of the lake, in January of 1976, was the same as was measured at the 4-m depth. Further information concerning the thermal simulations is presented in Part IV.

13. Since one of the sampling periods by the OCPCD coincided with the December sampling by Comp, the data were also used for initialization of the entire CE-QUAL-R1 model. Conditions were near isothermal at this time, so concentrations of constituents in the deeper layers were assumed to be the same as those occurring in the lowest layer measured. A summary of the initial conditions is given in Table 1.

14. Although the model allows for two algal assemblages, only one was used for the Lake Conway simulations. The UFDEE collected most of the phytoplankton data for the Lake Conway LSOMT, but their data concerning individual species were not in a form suitable for the CE-QUAL-R1 model. Their data were analyzed and reported as cells per millilitre; the model requires units of milligrams per litre. The volume for individual species would have to be measured in order to make the conversion.

15. Blancher,* using literature values for the volume of many of the species encountered in Lake Conway, obtained estimates of biomass for individual species. He then correlated the total of these estimates with the estimates of the total weight obtained from chlorophyll-a values. Because the resulting correlation was poor, it was decided not to use the two algal compartments with biomass estimates calculated from cell counts. Instead, estimates for biomass of the total algal community were calculated using OCPCD chlorophyll-a values and a conversion factor (i.e., 0.23 g/m^3 dry weight = 1 μg/ℓ chlorophyll-a) developed by Spangler (1969).

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* Personal Communication, Mar 1980, Marine Environmental Science Consortium, Mobile, Ala.

16. The nitrite-N, nitrate-N, and orthophosphate-P values reported for December of 1977 indicated that the quantity for these variables was below instrument detection limits of 0.01 mg/ℓ. In a separate study of the Middle pool from June of 1976 to October of 1977, Sompongse (1978) found most nitrite-N values to be between 0.001 and 0.003 mg/ℓ. An arbitrary value of 0.002 mg/ℓ was used as an initial value for all three compartments.

17. Fecal coliforms were not measured for the Lake Conway LSOMT, and an arbitrary value of zero was used for initial values. Since fecal coliforms do not interact with any other variable in the model, their values can be disregarded for the present evaluation.

18. Estimates of the mass for zooplankton and benthos came from the UFDEE. Zooplankton were estimated using the vertical haul technique, which gives an estimate of their biomass in units of grams per square metre. The assumption was made that the average depth where the samples were taken was 6 m, so the reported figure was divided by six to obtain the needed units of grams per cubic metre. Benthic macroinvertebrate data were reported in the required units of milligrams per square metre.

19. Estimates for the fish compartments came from a study (Guillory 1979) on the Middle pool by the FGFFC. Estimates were made using block net collections in the spring of 1977. Fish were apportioned between model compartments using food habit data supplied in Leidy and Jenkins (1977).

Model Coefficients

20. Initial estimates for the coefficients of the model were obtained from a previous model study within the WQMG (Ford et al. 1979), from studies performed at Lake Conway, and from Jorgensen (1979). Coefficients concerning the hydrothermal regime were calibrated using Comp's (1979) temperature data and the thermal portion of CE-QUAL-R1. Once these coefficients were estimated, they remained the same for the verification simulation of the thermal model as well as for the calibration of the entire CE-QUAL-R1 model. Other coefficients were calibrated

using data from the Lake Conway LSOMT. Calibration and verification are discussed in detail in Part IV and Part V. A list of the coefficients used in simulations is presented in Table 2.

Updates

21. Meteorological data needed by the model were daily values for the cloud cover fraction, dry bulb temperature, dew point temperature, air pressure, and wind speed. These data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Weather Station "Orlando WSO MCCOY," located approximately 3 km from the Middle pool. The measured 3-hr data for the variables were averaged over 24 hr to provide daily updates.

22. There are no stations recording inflow or outflow measurements at Lake Conway. Blancher (1979), in a study of the hydrologic budget for the 1976 water year, found the Lake Conway system to be precipitation and evaporation dominated. Since precipitation falling directly into the lake is not included in the model, and since no inflow measurements were available for the lake, rainfall (and storm water) was treated in the model as tributary inflow. From Blancher's (1979) measurements it was found that the total inflow into Lake Conway's system, attributable to precipitation, equalled 1.18 times the total rainfall falling directly into the lake. Using this factor and daily rainfall records obtained from the "Orlando WSO MCCOY" station, inflow due to precipitation was calculated. In addition, from Blancher's (1979) work and seepage studies by Fellows (1978), it was calculated that there was a positive seepage into Lake Conway, equal to approximately 0.02 m^3/sec. This constant figure was added to the inflow figure due to precipitation.

23. Besides the quantity of inflowing water, model input requirements include the concentrations of constituents that are carried along with the inflow. Algae and zooplankton concentrations were assumed to be zero. Coliform colonies were also set at zero since that variable was not of interest in the present study. The values used for other update variables (Table 3) were taken from Blancher (1979), Blancher and

Fellows (1979), Fellows (1978), and C. Hendry.* Temperature values used were arbitrarily set to follow the sinusoidal pattern of lake temperature.

24. Surface elevation at Lake Conway is regulated by a weir that is 26.2 m mean sea level (msl) (Fellows 1978). Data from the U. S. Geological Survey (Orlando, Fla.) showed that the lake surface never reached this elevation during the study year, so flow out of the lake was set to zero.

* Personal Communication, Mar 1980, University of Florida, Gainesville, Fla.

PART IV: THERMAL SIMULATIONS

Calibration

25. The thermal portion of CE-QUAL-R1 was calibrated with those coefficients dealing with the water budget and the hydrothermal regime. Coefficients concerning depth versus area and depth versus volume were obtained using data supplied by E. Blancher.* Coefficients for the hydrothermal regime were calibrated using data, measured monthly, from Comp (1979).

26. Blancher's estimate of lake surface area (2.99 km^2) and lake volume (17.9×10^6 m^3) corresponds to model estimates of 3.23 km^2 and 17.7×10^6 m^3, respectively. The water surface elevation was always within 0.3 m of measured values. The calibration results of the thermal regime are shown in Figure 2. The observed values were the average of six or seven observations taken over a 24-hr period, although not necessarily from midnight to midnight. Therefore, comparisons of predicted versus measured values may have been up to one day apart. The measured maximum versus minimum values for a particular layer over a day's period varied widely, ranging from less than 1° to 8.9°C (Table 4).

27. Comp's (1979) data show slight stratification began between the 10 February and 10 March sampling period. Although the model predicted periods of slight stratification and break-up in January and early February, the onset of a permanent stratification occurred in mid-February. Measured data show that the fall overturn, to a depth of 9 m, occurred between the 12 September and 6 October sampling dates. Fall overturn predicted by the model occurred during this same time.

Verification

28. Data used for verification were collected by the OCPCD.

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* Personal Communication, Dec 1979, Marine Environmental Science Consortium, Mobile, Ala.

Unfortunately, the data were reported as being collected for two or three days, making comparison with model preditions difficult. In addition, measurements were rarely taken below 5 m. Initialization values for the verification simulation were taken from the 26 and 27 January 1976 sampling period. Simulation was for a period of approximately 34 months, ending in October of 1978. Results of temperature prediction from the verification simulation are presented in Figure 3. In general, model predictions were similar to the measured data. The main difference was that the model prediction in the winter was slightly lower, and in the summer slightly higher, than measured data. The model predicted thermal stratification for the spring and summer of all three years. Unfortunately, not enough measured data were available to validate this phenomenon. The predictions for the water budget were also satisfactory. For the entire 34-month period, the predicted depth of water was within 0.5 m of values reported by the U. S. Geological Survey, Orlando, Fla.

PART V: ECOLOGICAL SIMULATIONS

29. Only the results from the final simulation will be presented herein. The initial conditions, coefficients, and updates used were those presented in Tables 1, 2, and 3, respectively. Simulations started on 18 December 1977 and continued to 30 November 1978 using a time step of one day.

30. Temperature predictions followed closely to the results presented in the section under calibrating the thermal model. There was intermittent stratification in January and February, with permanent stratification starting in early March. From April through September, a thermocline was predicted, starting at about 4 m in April and progressing to 9 m in September. Complete mixing to a depth of 12 m is predicted to occur in mid-October, with isothermal conditions occurring from then until the end of the simulation, 30 November 1978.

31. Oxygen is shown in the simulation to be greatly affected by thermal stratification. At the very bottom of the pool, oxygen is predicted to be zero from early March until mid-October, corresponding closely to thermal stratification. At about 9 m, which is the lowest depth for which measured data are available, the strata become anoxic from mid-March through late September. The data from Comp (1979) show a weak clinograde oxygen curve occurring during the March sampling period, becoming a strong clinograde curve between April and September. This same general pattern was predicted by the model. In the epilimnetic layers, because of mixing, little oxygen stratification occurs. The model prediction of oxygen concentration in the surface layer, along with the data from Comp (1979) and the OCPCD, is presented in Figure 4.

32. In parts of July, August, and September, the model predicts supersaturated concentrations of oxygen in the metalimnion. It appears that the metalimnetic oxygen maxima are due to algal photosynthesis immediately below the mixed layer. Photosynthesis appears to be stimulated because increased nutrient concentrations from the hypolimnion become available to the euphotic zone. The layers with increased oxygen concentration were always approximately 6 to 8 m deep, and usually at the

interface where the limiting factor changes from phosphorus to light. Algal concentrations in these zones were usually higher than those predicted to occur in the epilimnion.

33. Although there are no data from Lake Conway to support the model prediction of oxygen supersaturation (in part, because data are not routinely collected at the depth it is predicted to occur), Wetzel (1975) claims that metalimnion oxygen maxima occur in a large number of lakes. He cites figures from Eberly (1964) that show the average peak in oxygen concentration in over 50 lakes to be 17.2 mg/ℓ, and that concentrations of nearly 36 mg/ℓ have been recorded by Birge and Juday (1911). The metalimnetic oxygen maxima predicted by the model ranged from 10 to 21 mg/ℓ.

34. Predicted algal populations in the surface area ranged from 0.3 to 3.0 mg/ℓ (Figure 5) and were generally within the range of measured data. The vertical bars in Figure 5 represent data collected by Comp (1979), Conley et al. (1979), and the OCPCD. The only major peak in biomass that was predicted started in early October and corresponded in part to the fall overturn. The increase of available nutrients from the hypolimnion appears to have caused the predicted increase. Algal biomass predictions from 4 to 6 mg/ℓ were predicted in lower layers, usually at 6 to 9 m deep, in July, August, and September. These increased biomass figures corresponded to the metalimnetic oxygen maxima discussed earlier. Data from Comp (1979) also show increased biomass figures for deeper strata during his July-September collection periods.

35. Predictions of zooplankton biomass in the surface layer were within the minimum and maximum values measured (Figure 6). The highest prediction occurred near the end of the simulation and corresponded to the high prediction of phytoplankton. Zooplankton biomass in lower oxygenated waters generally followed the prediction in the surface layer. Since zooplankton are killed and added to the detritus compartment in anaerobic waters, predictions of zero occurred in those layers predicted to be without oxygen.

36. Nutrient predictions generally followed patterns as outlined in Wetzel (1975). Orthophosphate-P, ammonium-N, nitrite-N, and nitrate-N

all remained at generally low concentrations in the mixed layer, and increased in hypolimnetic waters during periods of stratification. Predictions of orthophosphate-P in the epilimnion generally ranged between 0.001 and 0.003 mg/ℓ, increasing to 0.5 mg/ℓ in the bottom of the pool. All reported OCPCD figures for orthophosphate-P were at the 0.01 detection limit. Most of the reported values for nitrite-N and nitrate-N were also at the 0.01 detection limit. Predicted nitrite-N in the surface layer ranged from 0.007 to 0.018 mg/ℓ and were as high as 0.47 mg/ℓ in the bottom layer. Predictions for nitrate-N in the surface area were between 0.001 and 0.018 mg/ℓ with a high in the bottom layer of 0.76 mg/ℓ. Measured ammonia-N values were usually reported at the detection limits of 0.05 mg/ℓ, except for a few slightly higher values in September, October, and November of 1978. The model predicted the ammonia-N in the surface area to be fairly constant, usually ranging from 0.02 to 0.03 mg/ℓ. In the bottom layer, predicted concentrations ranged as high as 3.5 mg/ℓ. Although this value is much higher than the reported figures by the OCPCD, Wetzel (1975) commented that ammonia-N in the anaerobic hypolimnetic waters of eutrophic lakes often reached levels above 10 mg/ℓ.

37. Values for other predicted variables appeared reasonable. Benthos predictions in the littoral zone ranged from 6,000 to 46,000 mg/m. The mean values for measured data ranged from 3,200 to 22,000 mg/m, although individual values greater than 50,000 mg/m were reported. Predicted values for the three fish compartments ranged from 5 to 76 kg/ha. Although no measured estimates were available for 1978, the values were generally in the range of data measured in 1976 and 1977 and reported by Guillory (1979). The only predicted values that appeared consistently different from measured values were for pH. Most of the predicted values ranged from 5.8 to 6.8, whereas most average values reported by Comp (1979) were 6.5 to 8.5, and by the OCPCD, 7.0 to 7.8.

PART VI: DISCUSSION

Data

38. The Lake Conway data set is not suitable for a proper evaluation of the CE-QUAL-R1 model. As mentioned earlier, the main reason for this is that the objective of the Lake Conway study was not to evaluate CE-QUAL-R1. The Lake Conway LSOMT was planned and the data were collected, analyzed, and reported before the decision was made to evaluate the model by simulating Lake Conway.

39. The major problems with the data were:

- *a*. Initialization values for the model should be collected on the same day. This was not done by the different contractors collecting data on Lake Conway.
- *b*. Because the lake thermally stratifies, processes and rates occurring in the epilimnion and hypolimnion differ markedly, with a concomitant change in the biomass of components in different layers. Very little data, collected on a regular basis, are from the hypolimnetic zone.
- *c*. To be able to adequately predict changes in an ecosystem, information should be available describing the structure and function of the system. The biomass of system components is a measure of the structure. The function is a measure of the interaction, such as photosynthesis, respiration, or decay. This point will be further explained in the section entitled "Flux." Little information concerning system function is available.
- *d*. Little information is available concerning nutrient dynamics since reported concentrations usually were at detection limits.
- *e*. Some of the data are questionable. For example, temperature fluctuations in the hypolimnion in June, at a depth of 9 m, varied over 8°C (Table 4). Temperatures should remain fairly stable in the hypolimnion. Another example concerns estimates for algae in the surface layer. The average algal concentration calculated from the OCPCD data for 1978 was 1.02 mg/ℓ. From Comp's (1979) data this figure was 0.72 mg/ℓ, and from the University of Florida it was 0.14 mg/ℓ. Although the data may not have been collected at the same time or at the same stations and therefore may have been different, the range of average values for the year is still questionable.

Flux

40. Algorithms are parts of the model that connect state variables, showing how they interact or function. Coefficients and updates are used in the algorithms to calculate how much interaction occurs, showing how much material flows from one state variable to another. This flow of material between variables is the flux.

41. Most information from the Lake Conway LSOMT concerned changes in standing stocks of state variables through time. Very little information was available on the fluxes or interaction between variables. Unfortunately, it is possible to use different sets of coefficents with the same initial conditions and make the same predictions. A simplified example of this is shown in Figure [illegible]. In each model there are four compartments, with the value for the initial conditions listed above the value for the final prediction. In both models, the final predicted values were the same even though the fluxes were different. Even though a model is calibrated using measured state variables for one period in time, the prediction by the model for another period in time may be incorrect if the initial conditions or updates are different. This same type of problem was shown to occur by Scavia (1980) using a model of Lake Ontario. Therefore, in order to ensure the best model for a particular ecosystem, calibration and verification procedures should include comparisons of measured versus predicted flux values as well as measured versus predicted values for state variables.

42. Computer code was added to the model to obtain estimates of the fluxes for all compartments containing nitrogen and phosphorus (Table 5). Unfortunately, no estimates of fluxes were available from the Lake Conway LSOMT for 1978. The productivity value was checked against values from a table supplied by Wetzel (1975) and was found to be in the range of values supplied for eutrophic lakes.

Model Assumptions

43. All models are, by definition, simplified representations of

the actual prototype. One of the benefits of this simplified representation is that the model can be manipulated for less cost and in a shorter time than experimentation on the prototype. One of the costs associated with this benefit is that a number of assumptions are used in order to simplify the real system, and these assumptions, then, impose limitations on the use and interpretation of model results. The major assumptions and limitations of the present version of CE-QUAL-R1 are presented below.

One-dimensional assumption

44. A lake can be represented by a vertical series of completely mixed horizontal layers. Thus, only the vertical dimension is retained during computation, and concentration gradients occur only in one direction. Therefore, all concentrations of water quality constituents in any given layer are parallel to the water surface both laterally and longitudinally. Because of this constraint, the model cannot predict differences in concentrations occurring in different parts of the lake. In addition, all inflow and outflow quantities and concentrations are instantaneously dispersed and homogeneously mixed throughout each horizontal layer. This assumption should not affect the Middle pool of Lake Conway as much as most reservoirs, but it must be kept in mind when simulating larger lakes with coves and embayments, especially if nutrient point sources are present.

Density function

45. The density of water is assumed to be only a function of temperature. Contributions to water density by suspended and dissolved solids are not currently included in the model. Any model application in which the suspended and dissolved solids contribute substantially to the density of water could be questioned. This assumption is not very significant for the present study since measured values for suspended and dissolved solids are low.

Simplified ecology

46. Many of the biological species that exist in a lake can be lumped together for modeling purposes. In all cases the aggregation is quite severe--one compartment each for all zooplankton and benthic

species, two compartments for all algal species, and three compartments for selected fish species. Because of this aggregation, individual species dynamics and interactions within the ecosystem cannot be considered. This is a difficult assumption to assess and can only be determined by repeated model verification.

Conservation of mass

47. The dynamics of each biological and chemical component can be described by conservation of mass. The mass of elements such as carbon, oxygen, nitrogen, and phosphorus is accounted for by considering the inflows, outflows, and internal changes in the form of the elements, which are neither created nor destroyed.

48. Results from the study have shown that this assumption has been violated, probably due to the interaction between the algorithms, the time step and the solution scheme, hereafter referred to only as the solution scheme. For a conservative substance, such as total dissolved solids, the results are satisfactory when using a one-day time step. But for nonconservative substances such as nitrogen or phosphorus, mass is not satisfactorily conserved with a time step of one day. At present, the model solves equations dealing with each state variable in a sequential manner. In effect, this scheme solves coupled differential equations in an uncoupled manner. Under certain conditions, more material is predicted to leave a compartment than is contained in the compartment, which causes a mass imbalence.

49. On those occasions when more material is predicted to leave a compartment than is available, the model arbitrarily changes the predicted negative concentration to either zero or a small positive concentration. This, in effect, creates mass which can then be used by other compartments in the model just as if the addition entered the lake along with the upstream flow. During the Lake Conway application, these arbitrary changes, termed the negative hedge, were totaled in order to assess their significance.

50. During the calibration of the model, it was noticed that the negative hedge was very sensitive to three coefficients: the algae settling rate, the algae half-saturation coefficient, and the zooplankton

assimilation rate. Three simulations were made with exactly the same data set except for minor changes for these three coefficients. The algae half-saturation coefficient was varied from 0.005 to 0.003, the algae settling rate from 0.4 to 0.2, and the zooplankton assimilation from 0.33 to 0.27. All of these variables are reasonable and can be found in Jorgensen (1979). The effect of these changes on selected output predictions can be seen in Table 6. The "A" simulation is the base run for Lake Conway and was used in the section entitled "Ecological Simulations." The "B" and "C" simulations have minor coefficient changes. As can be seen, the phosphorus added in the "A" simulation, by way of the negative hedge, was nearly the same as the total phosphorus inflow. The "B" and "C" simulations became progressively worse. For nitrogen, the value was actually greater.

51. To get an idea of the possible effect of this addition due solely to the solution scheme, the negative hedge values were compared to nitrogen and phosphorus dangerous loading amounts (Vollenweider 1968). The dangerous loading amount for nitrogen is approximately 2.0 $g/m^2/yr$ and for phosphorus 0.13 $g/m^2/yr$. Comparative figures for nitrogen from the three simulations are 4.9, 194, and 890 $g/m^2/yr$. For phosphorus the figures are 0.22, 8.2, and 39.6 $g/m^2/yr$. Thus, based on the loadings due to the negative hedge, eutrophic conditions would be expected. This appears to be substantiated by the maximum amount of algae in the surface layer for the three simulations: 3.05, 57.3, and 326.6 mg/ℓ. Predictions of time histories for algae in the surface layer for the three simulations can be found in Figure 8. This evidence tends to show that the predictions may be driven by the solution scheme rather than by the algorithms, coefficients, and updates. This condition is totally unreasonable and leads to the suspicion of model predictions. It is recommeded that the solution scheme be changed before use of CE-QUAL-R1 by the APCRP. This problem is currently being corrected as part of the EWQOS Program.

Kinetic principle

52. The kinetic principle implies that internal changes that occur in the lake do so through processes such as ingestion, respiration,

and photosynthesis. This assumption should not adversely affect the interpretation of model predictions.

Aerobic environment

53. Chemical and biological processes occur in an aerobic environment. While CE-QUAL-R1 does incorporate simple default rate coefficients when dissolved oxygen approaches zero, the model predictions are not realistic under anaerobic conditions. This assumption results in the inability to simulate the buildup of a dissolved oxygen deficit under anaerobic conditions. Also, the changes in the solubility and formation of various chemical species and interactions between the sediment and water under anaerobic conditions cannot be simulated. This assumption probably had some effect on predictions since anaerobic conditions were present in the hypolimnion, but because the Middle pool is relatively shallow, these effects should be minimal. An anaerobic subroutine is currently being developed as part of the EWQOS Program.

Ice-free environment

54. The model does not contain an ice cover algorithm. Model predictions are therefore limited to ice-free periods. This assumption had no effect on the Lake Conway simulation, and the assumption should be eliminated in the future with the addition of an ice cover algorithm, which is being planned as part of the EWQOS Program.

All inclusive variables

55. All of the components in a reservoir are represented in the model, unless they do not interact significantly with modeled variables. As noted above, these components may be lumped together, but it is assumed that they are included. Since macrophytes and their associated epiphytes were not included in the model, and since they affect other variables, the addition of macrophytes and epiphytes would change the present predictions. Fontaine (1978) estimated that planktonic gross production was only 38 percent of community gross production. By implication, the remainder of the photosynthesizing community supports 62 percent of gross production and may severely affect oxygen and nutrient concentrations. Part of this problem may be mollified by the fact that the model was calibrated using measured data, and algal coefficients,

for example, may have been set in such a manner as to include some effects attributable to macrophytes.

56. It is recommended that a macrophyte algorithm be included in the model before use by the APCRP. Since one of the recommendations from a workshop concerning the modeling of aquatic macrophytes was that a macrophyte algorithm be spatially variable in the vertical direction (Wlosinski 1981), this should pose no serious problem.

Inflow placement

57. The vertical placement of inflowing water within the lake is determined by temperature only. The density of an inflow is determined from its temperature, and it is placed into the horizontal zone of comparable density. Contributions to the density of the inflow by suspended and dissolved solids are not currently included in the model. In addition, all water entering the lake is from inflowing water. In the present study, the greatest portion of water entering the lake was from rain falling directly on the lake. Unless values for temperature of inflowing water are set at or above surface temperature, rainfall, with its associated nutrients, can be added to the wrong layer. Since the ratio of rainfall to lake volume is usually small, this problem should not be very significant, but should be corrected for realism.

Diffusion mechanism

58. Internal dispersion of thermal energy and mass is accomplished by an effective diffusion mechanism that combines the effects of molecular diffusion, turbulent stirring and mixing, and thermal convection. The transport is therefore assumed to be proportional to an effective diffusion coefficient and a concentration gradient. It is important to note that, although the diffusion gradient among layers is based on the concentration differences of the individual constituents such as dissolved oxygen or nitrate, the effective diffusion coefficient is always based on temperature. In many instances, mass diffusion coefficients may not be equivalent to thermal diffusion coefficients. The impact of this assumption should not be as great after the incorporation of an integral energy algorithm planned as part of the EWQOS Program.

Model Development

59. The CE-QUAL-R1 model is currently being improved as part of the EWQOS Program. Current developments and future changes will affect the compartments dealing with phytoplankton, zooplankton, benthos, sediment, pH, carbon dioxide, suspended solids, temperature, and fish. Plans have been made to add algorithms dealing with ice cover, anaerobic processes and macrophytes, and to change the solution scheme. In addition, the model may be run in a stochastic fashion; graphical output is being improved, and a user's manual (U. S. Army Engineer Waterways Experiment Station, in preparation) is being prepared. All of these changes should enhance the use of CE-QUAL-R1 in the APCRP.

Use of CE-QUAL-R1 in the APCRP

Technical considerations

60. The main objective of this study was to evaluate the use of the CE-QUAL-R1 model by the APCRP. Major negative comments concerning use of the present version of the model for simulating Lake Conway include problems dealing with the solution scheme, the lack of a macrophyte subroutine, and the lack of suitable data that did not allow an appropriate evaluation or verification. Positive comments include the fact that verification of the thermal portion of the model and predictions for water quality variables were satisfactory, and a number of model enhancements, two of which should nullify the first two negative comments, are currently being implemented. It is believed that the model would be a benefit to the APCRP after the solution scheme is improved and a macrophyte subroutine is added.

61. The model is also being evaluated for the EWQOS Program, and results from that study should be evaluated as they become available, keeping in mind differences between reservoirs and lakes. The differences between lakes and reservoirs, outlined by Baxter (1977), did not pose problems for the present model application.

62. The diffusivity approach for predicting temperature in the

version of the model being evaluated is not as appropriate for shallow lakes as compared to deep reservoirs,* but this possible problem should be improved with the incorporation of an integral energy algorithm explained in Stefan and Ford (1975) and Ford and Stefan (1980).

63. Two other possible problems are noted: (a) in the model, the sediment layer in shallow areas is not affected by the wind, whereas in shallow lakes this effect can be very important; and (b) the model output most closely fits those conditions found in the deepest part of the pool (U. S. Army Engineer Waterways Experiment Station, in preparation). In a reservoir, the deepest area is usually near the outlet structure, whereas in a lake situation it is usually near the center of the pool. If water quality in the downstream flow is of interest to the user, the predictions from the model may be reasonable for a reservoir but possibly not for a lake.

Resource considerations

64. Lake simulation using CE-QUAL-R1 requires a major effort by a multidisciplinary team. This effort includes data acquisition and manipulation into a form suitable for modeling, model calibration, and analysis of model simulations. It is estimated that each of these major steps would take a minimum of a few man-weeks and may need many man-months, especially for the first time the model is used by a particular staff.

65. The model requires a computer capable of handling 19 scratch files. Memory requirements for the thermal portion of the model are 23K words, and 54K words for the entire model. Compilation costs on the WES Honeywell 635 computer, using standard day rates, are approximately $9.00 for the thermal portion and $20.00 for the entire model. Execution cost for the thermal portion for a one-year simulation is $9.00 and for a three-year simulation, $17.00. Execution of the entire model for a one-year period is approximately $40.00.

* Personal Communication, Jan 1980, Dr. Dennis E. Ford, Hydrologist, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

66. Conclusions and recommendations are presented below:

a. The total Lake Conway data set was not in the most suitable form for use in evaluating CE-QUAL-R1. Because the Lake Conway data-collection program was designed for a different purpose, collection times by different contractors were not the same, few samples were taken in the hypolimnion, and little information was available on system function.

b. Verification of the thermal portion of the model, based on limited data, showed temperature predictions that were considered satisfactory.

c. Predictions of the model from the final calibration simulations were considered satisfactory.

d. The CE-QUAL-R1 model would be useful to the APCRP in predicting modeled water quality variables after problems dealing with the solution scheme have been remedied and a macrophyte algorithm has been added. All current model developments within the EWQOS Program should enhance model use of the APCRP. Other possible improvements that should be considered include output dealing with system function, nutrient input via rainfall, and effect of wind on sediments.

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Table 1

Initial Conditions for Ecological Simulations

Elevation, m	Algae 1 (ALGAE1),* mg/ℓ	Alkalinity (ALK), mg/ℓ	Benthos (BEN), mg/m^2	Ammonia (NH3), mg/ℓ N	Nitrite (NO2), mg/ℓ N	Nitrate (NO3), mg/ℓ N	Fecal Coliforms (COL) colonies/100 ml	Detritus (DET), mg/ℓ	Dissolved Organics (DOR) mg/ℓ	Dissolved Oxygen (DO) mg/ℓ	Orthophosphate (PO4) mg/ℓ P	Organic Sediment (SED) mg/m^2	Temperature (TEMP), °C	Total Dissolved Solids (TDS), mg/ℓ	Zooplankton (ZOO), mg/ℓ	pH (PH)
11-12	1.2	37	14000	0.063	0.002	0.002	0	0.4	0.93	9.3	0.002	1040000	18.6	154	0.05	7.3
10-11	1.4	37	14000	0.068	0.002	0.002	0	0.4	0.80	9.1	0.002	1040000	18.8	154	0.05	7.4
9-10	1.6	37	14000	0.070	0.002	0.002	0	0.4	0.70	8.9	0.002	3120000	18.8	153	0.05	7.5
8-9	1.3	38	14000	0.063	0.002	0.002	0	0.4	0.85	8.8	0.002	3120000	18.6	138	0.05	7.4
7-8	1.0	38	14000	0.056	0.002	0.002	0	0.4	0.96	8.8	0.002	3120000	18.5	123	0.05	7.3
6-7	0.9	38	14000	0.056	0.002	0.002	0	0.4	0.96	8.8	0.002	3120000	18.4	123	0.05	7.3
5-6	0.75	38	14000	0.056	0.002	0.002	0	0.4	0.96	8.8	0.002	3120000	18.2	123	0.05	7.3
4-5	0.75	38	14000	0.056	0.002	0.002	0	0.4	0.96	8.8	0.002	3120000	18.2	123	0.05	7.3
3-4	0.75	38	14000	0.056	0.002	0.002	0	0.4	0.96	8.8	0.002	3120000	18.2	123	0.05	7.3
2-3	0.75	38	14000	0.056	0.002	0.002	0	0.4	0.96	8.8	0.002	3120000	18.2	123	0.05	7.3
1-2	0.75	38	14000	0.056	0.002	0.002	0	0.4	0.96	8.8	0.002	3120000	18.2	123	0.05	7.3
0-1	0.75	38	14000	0.056	0.002	0.002	0	0.4	0.96	8.8	0.002	3120000	18.2	123	0.05	7.3

* Acronym in parentheses represents the variable name used in CE-QUAL-R1.

Table 2

Coefficients for Simulations

Parameter	Coefficient
Physical coefficients	
Turbidity factor (TURB)*	2.4
Evaporative wind function (AA+BB*WIND)	
AA	2.1E-9 m/(sec-mb)
BB	1.05E-9 mb^{-1}
Mixing coefficients	
Stability parameter (GSWH)	0.00004 sec^{-2}
Wind mixing coefficient (A1)	0.00001 m^2/sec
Hypolimnetic diffusivity (A2)	0.000002 m^2/sec
Metalimnetic coefficient (A3)	-0.5
Extinction coefficient (EXCO)	0.40 m^{-1}
Surface radiation fraction (SURFACE)	0.5
Critical advective density (CDENS)	1.0 kg/m^3
Reaeration coefficients	
Oxygen (DMO2)	2.04E-09 m^2/sec
Carbon dioxide (DMCO2)	2.04E-10 m^2/sec
Stoichiometry	
O2 - NH3 (O2NH3)	3.5
O2 - NO2 (O2NO2)	1.2
O2 - Detritus (O2DET)	2.0
O2 - Respiration (O2RESP)	1.6
O2 - Algal Biomass (O2FAC)	1.6
CO2 - Dissolved organic (CO2DOR)	0.2
Decay rates	
Dissolved organics (TDORDK)	0.15 per day
Ammonia (TNH3DK)	0.18 per day
Nitrite (TNO2DK)	0.40 per day

(Continued)

* Acronym in parentheses represents the variable name used in CE-QUAL-R1.

(Sheet 1 of 5)

Table 2 (Continued)

Parameter	Coefficient
Decay rates (cont'd)	
Coliforms	
(Q10)	1.04
(TCOLDK)	1.4 per day
	ALGAE 1 I = 1
Algae	
Chemical composition	
Carbon	0.45
Nitrogen	0.08
Phosphorus	0.011
Gross production rate (TPMAX(I))	1.45 per day
Temperature rate multipliers	
Lower threshold (T1)	0°C
Optimum (T2)	15°C
Optimum (T3)	30°C
Upper threshold (T4)	36°C
Half-saturation coefficients	
Carbon (PS2CO2(I))	0.1 mg/ℓ
Nitrogen (PS2N(I))	0.010 mg/ℓ
Phosphorus (PS2PO4(I))	0.005 mg/ℓ
Light (PS2L(I))	3.8 kcal/m^2/hr
Respiration rate (TPRESP)	0.17 per day
Settling rate (TSETL(I))	0.40 m/day
Self-shading coefficient	0.070 per m-mg/ℓ
Zooplankton	
Chemical composition	
Carbon	0.45
Nitrogen	0.08

(Continued)

(Sheet 2 of 5)

Table 2 (Continued)

Parameter	Coefficient
Zooplankton (cont'd)	
Phosphorus	0.012
Assimilation rate (TZMAX)	0.330 per day
Temperature rate multipliers	
Lower threshold (T1)	0°C
Optimum (T2)	20°C
Optimum (T3)	26°C
Upper threshold (T4)	36°C
Assimilation efficiency (ZEFFIC)	0.65
Feeding preference	
Algae 1 (PREF(1))	0.85
Algae 2 (PREF(2))	0.0
Detritus (PREF(3))	0.15
Half-saturaton coefficient (ZS2P)	0.3 mg/ℓ
Mortality rate (TZMORT)	0.010 per day
Respiration rate (TZRESP)	0.2 per day
Detritus	
Chemical composition	
Carbon	0.32
Nitrogen	0.07
Phosphorus	0.009
Settling rate (TDSETL)	0.25 m/day
Decay rate (TDETDK)	0.011 per day
Sediment	
Decay rate (TSEDDK)	0.00008 per day
Benthos	
Chemical composition	
Carbon	0.47
Nitrogen	0.08
Phosphorus	0.011

(Continued)

(Sheet 3 of 5)

Table 2 (Continued)

Parameter	Coefficient
Benthos (cont'd)	
Assimilation rate (TBMAX)	0.043 per day
Temperature rate multipliers	
Lower threshold (T1)	0°C
Optimum (T2)	20°C
Optimum (T3)	26°C
Upper threshold (T4)	36°C
Assimilation efficiency (BEFFIC)	0.6
Half-saturation coefficient (BS2SED)	200 mg/m^2
Mortality rate (TBMORT)	0.020 per day
Respiration rate (TBRESP)	0.016 per day

	Coefficient		
	FISH 1 I = 1	FISH 2 I = 2	FISH 3 I = 3
Fish			
Chemical composition			
Carbon	0.45	0.45	0.45
Nitrogen	0.08	0.08	0.08
Phosphorus	0.011	0.011	0.011
Assimilation rate (TFMAX(I))	0.009 per day	0.081 per day	0.014 per day
Temperature rate multipliers			
Lower threshold (T1)	0°C	0°C	0°C
Optimum (T2)	25°C	25°C	25°C
Optimum (T3)	29°C	29°C	29°C
Upper threshold (T4)	35°C	35°C	35°C
Assimilation efficiency (FEFFIC)	0.8	0.8	0.8
Half-saturation coefficients			
Fish (FS2FSH)	5.7 kg/ha	-	-

(Continued)

Table 2 (Concluded)

Parameter	Coefficient FISH 1 I = 1	FISH 2 I = 2	FISH 3 I = 3
Fish (cont'd)			
Zooplankton - detritus (FS2ZOO)	-	4.5 mg/ℓ	-
Benthos - sediment (FS2BEN)	-	-	7.0 mg/ℓ
Fraction of diet			
Sediment (F3SEC)			0.001
Benthos (F3BEN)			0.999
Mortality rate (TFMORT)	0.001 per day	0.001 per day	0.001 per day
Respiration rate (TFRESP)	0.008 per day	0.008 per day	0.008 per day

(Sheet 5 of 5)

Table 3

Water Quality Update Variables

Parameter	Update												
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ALG 1, mg/ℓ	0	0	0	0	0	0	0	0	0	0	0	0	0
ALK, mg/ℓ	37.0	36.0	35.0	36.0	37.0	37.0	37.0	38.0	37.0	38.0	39.0	37.0	37.0
BOD, mg/ℓ	0.7	1.7	0.98	1.4	0.32	0.6	0.7	0.9	0.2	0.4	0.8	0.6	0.3
NH4-N, mg/ℓ	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
NO2-N, mg/ℓ	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
NO3-N, mg/ℓ	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
COL, colonies/100 ml	0	0	0	0	0	0	0	0	0	0	0	0	0
DET, mg/ℓ	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
DO, mg/ℓ	9.2	9.9	9.6	8.3	8.0	8.0	7.9	7.7	7.9	8.4	8.5	8.7	9.2
PO4-P, mg/ℓ	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
TEMP, °C	18.0	14.0	16.0	24.0	26.0	26.0	27.0	28.0	27.0	23.0	22.0	21.0	18.0
TDS, mg/ℓ	157.0	153.0	120.0	143.0	124.0	130.0	135.0	146.0	140.0	140.0	137.0	129.0	107.0
ZOO, mg/ℓ	0	0	0	0	0	0	0	0	0	0	0	0	0
PH	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8

Table 4

Minimum and Maximum Temperature Readings from the Middle Pool of Lake Conway*

	18-19 Dec 77		13-14 Jan 78		10-11 Feb 78		10-11 Mar 78		14-15 Apr 78		19-20 May 78	
Depth, m	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
0-1	18.1	19.0	13.5	14.3	12.1	13.0	15.5	16.5	23.8	24.3	26.2	27.8
1-2	18.5	19.0	13.5	14.2	12.2	12.5	15.7	16.5	23.8	24.4	26.4	27.0
2-3	18.5	19.2	13.5	14.0	12.2	12.5	15.7	16.2	23.8	24.4	26.4	27.0
3-4	18.3	19.0	13.5	14.0	12.2	12.5	15.7	16.2	23.8	24.3	26.3	27.1
4-5	18.2	19.0	13.5	14.0	12.0	12.5	15.7	16.2	23.8	24.3	26.0	26.7
5-6	18.0	18.8	13.5	14.0	12.0	12.5	15.6	16.2	22.5	24.3	25.8	26.6
6-7	18.0	18.6	13.5	14.0	12.0	12.5	15.5	16.2	20.0	24.3	25.2	25.6
7-8	18.0	18.5	13.5	14.0	12.0	12.5	15.5	16.2	18.8	21.5	23.7	25.0
8-9	18.0	18.5	13.5	13.9	12.0	12.5	15.2	15.9	18.2	19.5	22.0	23.4
9-10	18.0	18.5	13.5	13.9	12.0	12.5	15.0	15.5	18.2	18.8	21.3	22.0

(Continued)

* Data taken during a study by G. Comp, University of Florida, Gainsville. Values expressed in degrees Celsius.

Table 4 (Concluded)

Depth, m	23-24 Jun 78		29-30 Jul 78		17-18 Aug 78		12-13 Sep 78		6-7 Oct 78		3-4 Nov 78	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
0-1	25.9	29.5	28.0	29.5	30.1	32.0	29.2	30.0	21.5	27.5	22.3	23.7
1-2	25.1	28.5	28.0	29.5	30.1	31.5	29.2	29.8	24.5	27.5	22.3	23.7
2-3	24.1	28.5	28.0	29.0	30.0	31.4	29.3	29.6	22.0	27.5	22.3	23.7
3-4	23.9	28.0	28.0	29.0	29.5	31.1	29.2	29.6	21.5	27.3	21.7	23.7
4-5	23.8	28.0	28.0	29.0	29.5	31.0	29.0	29.6	22.0	27.2	21.7	24.0
5-6	23.5	28.0	28.0	29.0	29.0	29.0	29.0	29.6	22.0	27.2	21.7	23.7
6-7	23.5	27.5	28.0	29.0	28.5	29.0	29.0	29.5	22.0	27.0	21.7	23.7
7-8	23.2	27.3	28.0	29.0	27.5	28.2	28.8	29.3	22.0	27.0	21.7	23.6
8-9	23.0	26.2	27.5	28.7	27.0	27.7	27.5	28.6	22.5	27.0	21.7	23.6
9-10	17.0	25.9	25.5	27.0	25.5	26.7	26.5	27.5	23.0	27.0	21.7	23.6

Table 5

Predicted Fluxes Dealing with the Internal Cycling of Nitrogen and Phosphorus in Lake Conway

From	To	Pathway	Amount*
		Algae (dry weight)	
Nutrients	Algae	Photosynthesis	0.24×10^{9}
Algae	Nutrients	Respiration	0.12×10^{9}
Algae	Sediment	Settling	0.60×10^{8}
Algae	Zooplankton	Herbivory	0.53×10^{8}
		Zooplankton (dry weight)	
Algae + detritus	Zooplankton	Ingestion	0.57×10^{8}
Zooplankton	Nutrients	Respiration	0.35×10^{8}
Zooplankton	Detritus	Nonpredatory mortality	0.19×10^{7}
Zooplankton	Fish	Predatory mortality	0.40×10^{6}
Zooplankton	Detritus	Egestion	0.19×10^{8}
		Benthic Invertebrates (dry weight)	
Detritus	Benthos	Ingestion	0.18×10^{9}
Benthos	Nutrients	Respiration	0.42×10^{8}
Benthos	Sediment	Nonpredatory mortality	0.55×10^{8}
Benthos	Fish	Predatory mortality	0.50×10^{7}
Benthos	Sediment	Egestion	0.80×10^{8}
		Fish (dry weight)	
Benthos + sediment + detritus + zooplankton	Fish	Ingestion	0.11×10^{8}
Fish	Detritus	Egestion	0.22×10^{7}
Fish	Nutrients	Respiration	0.70×10^{7}
Fish	Sediment	Nonpredatory mortality	0.87×10^{5}
		Detritus + Sediment (dry weight)	
Algae	Sediment	Settling	0.60×10^{8}
Zooplankton	Detritus	Egestion	0.20×10^{8}
Zooplankton	Detritus	Nonpredatory mortality	0.20×10^{8}
Benthos	Detritus	Nonpredatory mortality	0.56×10^{8}
Fish	Detritus	Egestion	0.26×10^{7}
Fish	Sediment	Nonpredatory mortality	0.87×10^{5}
Detritus + sediment	Nutrients	Decay	0.29×10^{8}
Detritus + sediment	Fish	Detritivory	0.56×10^{7}
Detritus	Zooplankton	Detritivory	0.89×10^{7}
Sediment	Benthos	Detritivory	0.10×10^{9}

(Continued)

* All amounts are in kilograms for the entire lake for the entire simulation period.

Table 5 (Concluded)

From	To	Pathway	Amount
		Nitrite-N	
Nitrite-N	Nitrate-N	Decay	0.48×10^{7}
Ammonia-N	Nitrite-N	Decay	0.48×10^{7}
		Nitrate-N	
Nitrite-N	Nitrate-N	Decay	0.48×10^{7}
Nitrate-N	Algae	Photosynthesis	0.55×10^{7}
		Ammonia-N	
Ammonia-N	Algae	Photosynthesis	0.14×10^{8}
Ammonia-N	Nitrite-N	Decay	0.48×10^{7}
Algae	Ammonia-N	Respiration	0.10×10^{8}
Detritus + sediment	↓	Decay	0.20×10^{7}
Zooplankton	↓	Respiration	0.28×10^{7}
Fish	↓	Respiration	0.56×10^{6}
Benthos	↓	Respiration	0.34×10^{7}
		Orthophosphate-P	
Orthophosphate-P	Algae	Photosynthesis	0.26×10^{7}
Algae	Orthophosphate-P	Respiration	0.14×10^{7}
Detritus + sediment	↓	Decay	0.26×10^{6}
Zooplankton	↓	Respiration	0.42×10^{6}
Fish	↓	Respiration	0.77×10^{5}
Benthos	↓	Respiration	0.46×10^{6}

Table 6

Selected Values Dealing with the Negative Hedge from Three Simulations

		Simulation*		
	Units	A	B	C
Algae P half-saturation coefficient	mg/ℓ	0.005	0.004	0.003
Algae settling rate	m/day	0.4	0.3	0.2
Zooplankton assimilation rate	days	0.33	0.30	0.27
Total initial nitrogen	kg/lake	0.56×10^6	0.56×10^6	0.56×10^6
Total initial phosphorus	kg/lake	0.72×10^5	0.72×10^5	0.72×10^5
Total nitrogen inflow	kg/lake/348 days	0.69×10^4	0.69×10^4	0.69×10^4
Total phosphorus inflow	kg/lake/348 days	0.71×10^3	0.71×10^3	0.71×10^3
Total final nitrogen	kg/lake	0.59×10^6	0.75×10^6	0.14×10^7
Total final phosphorus	kg/lake	0.76×10^5	0.97×10^5	0.18×10^6
Nitrogen negative hedge	kg/lake/348 days	0.15×10^5	0.59×10^6	0.27×10^7
Phosphorus negative hedge	kg/lake/348 days	0.68×10^3	0.25×10^5	0.12×10^6
Highest algal concentration (surface)	mg/ℓ	3.05	57.3	326.6

* See paragraph 50 for explanation of simulations.

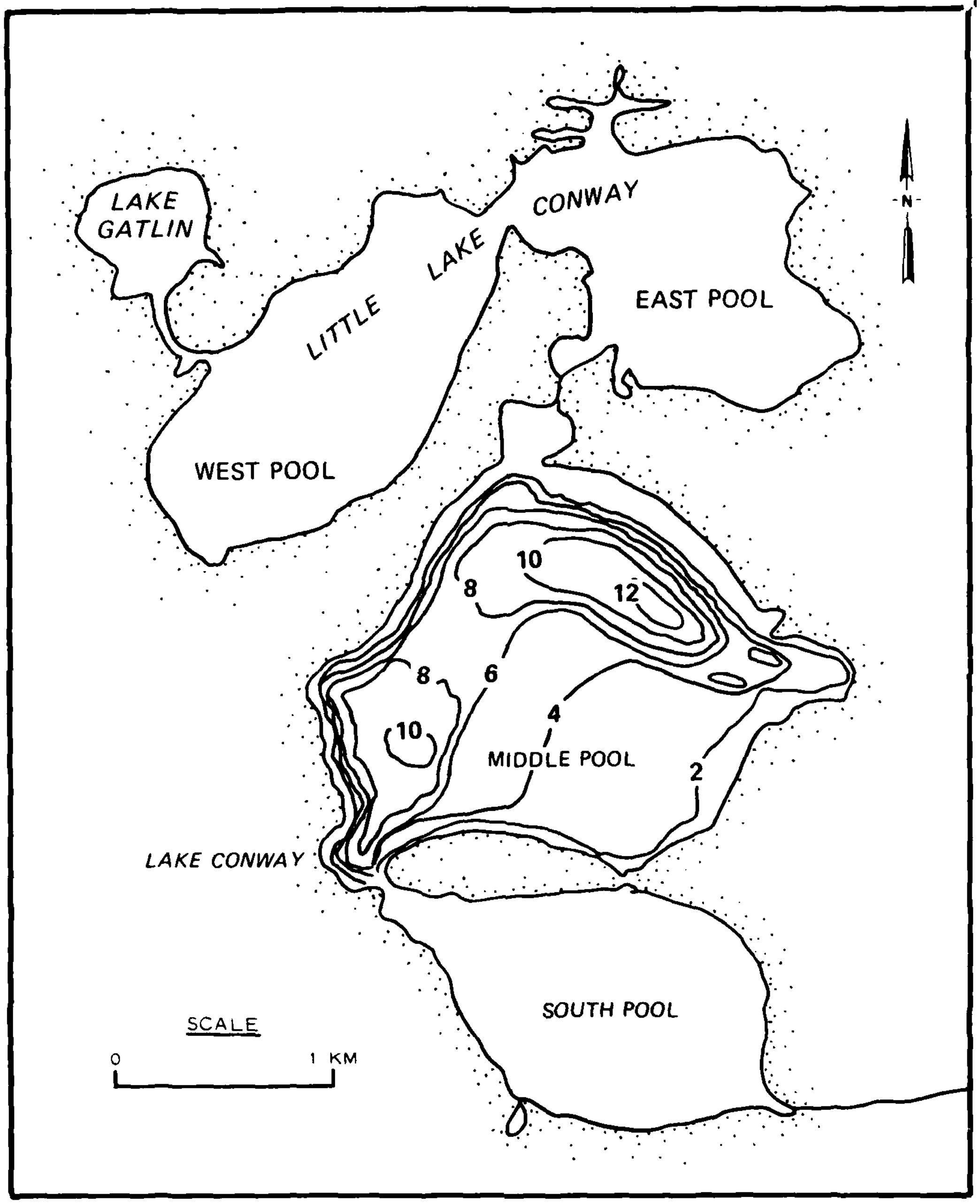


Figure 1. The Lake Conway system. Contour intervals are metres from the surface

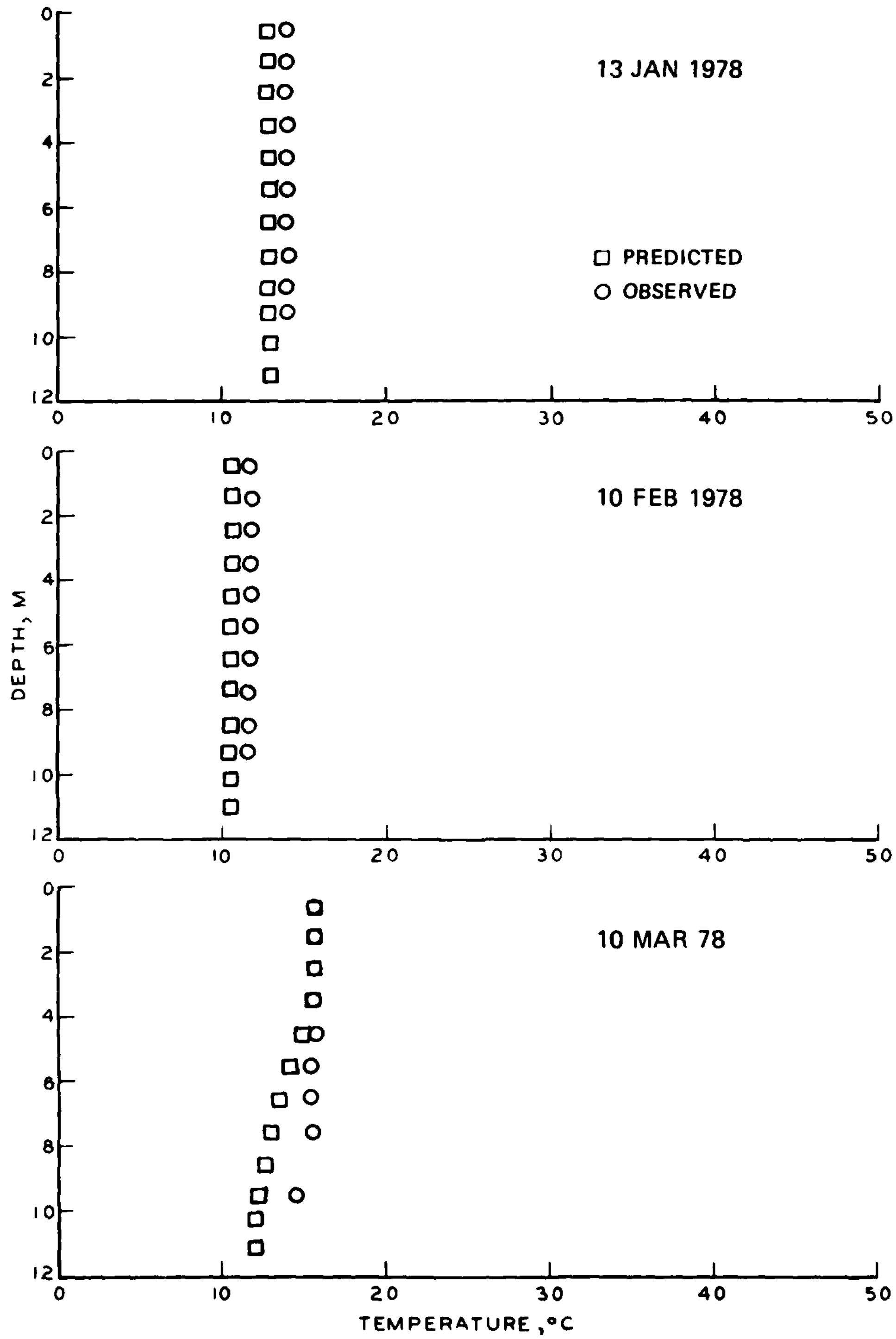


Figure 2. Temperature predictions from the calibration simulations of the thermal portion of CE-QUAL-R1 (Sheet 1 of 4)

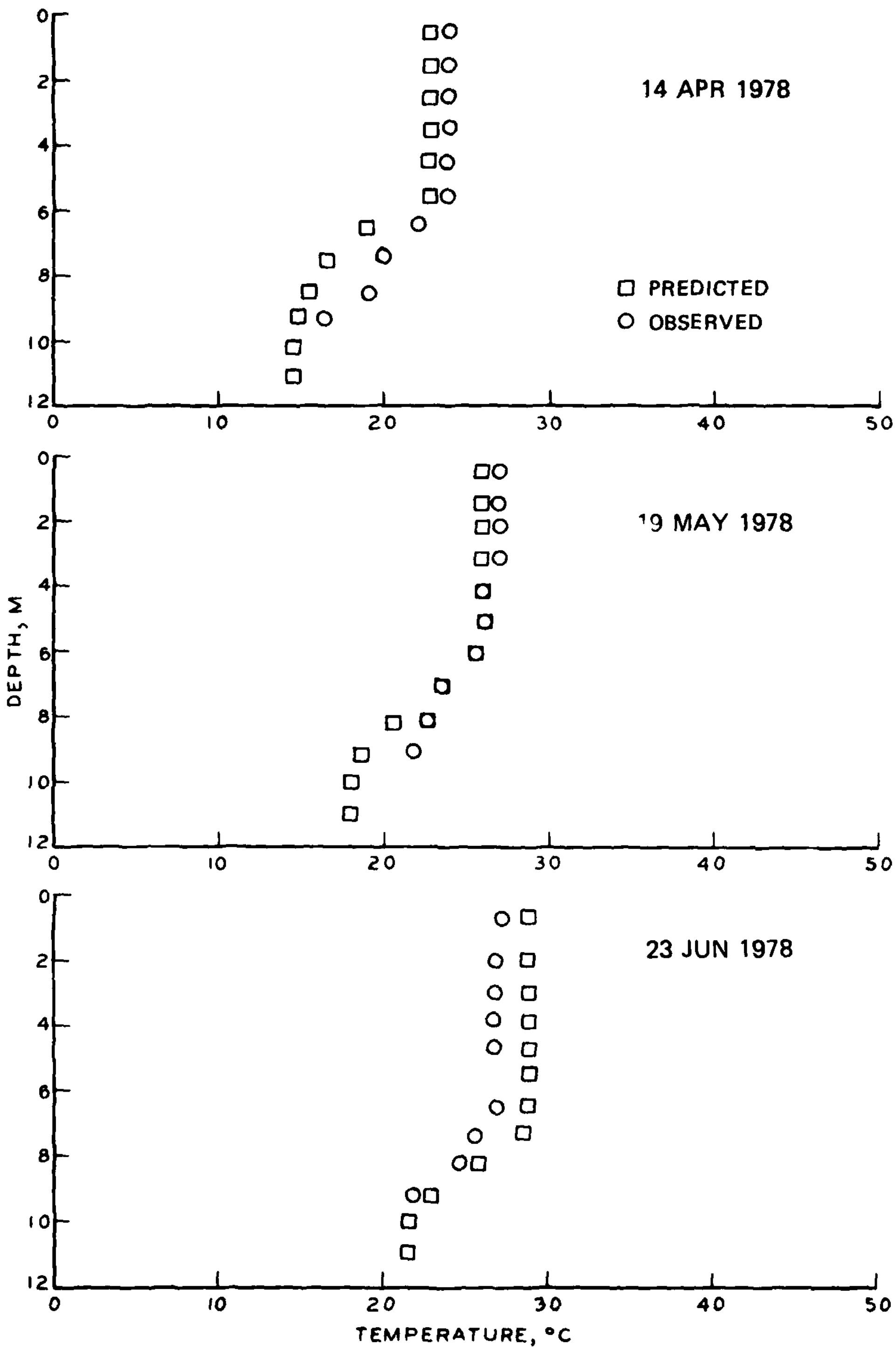
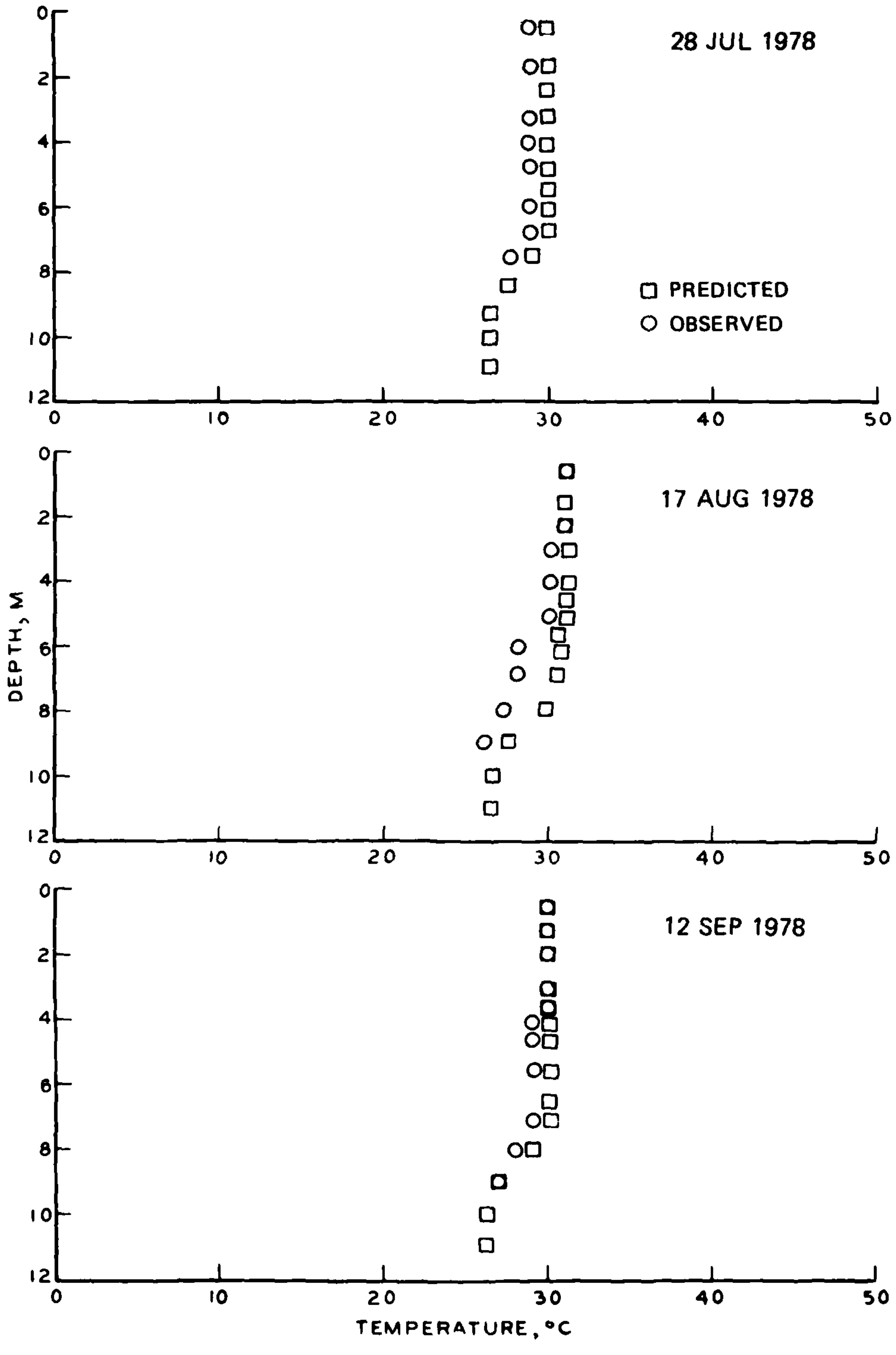


Figure 2. (Sheet 2 of 4)



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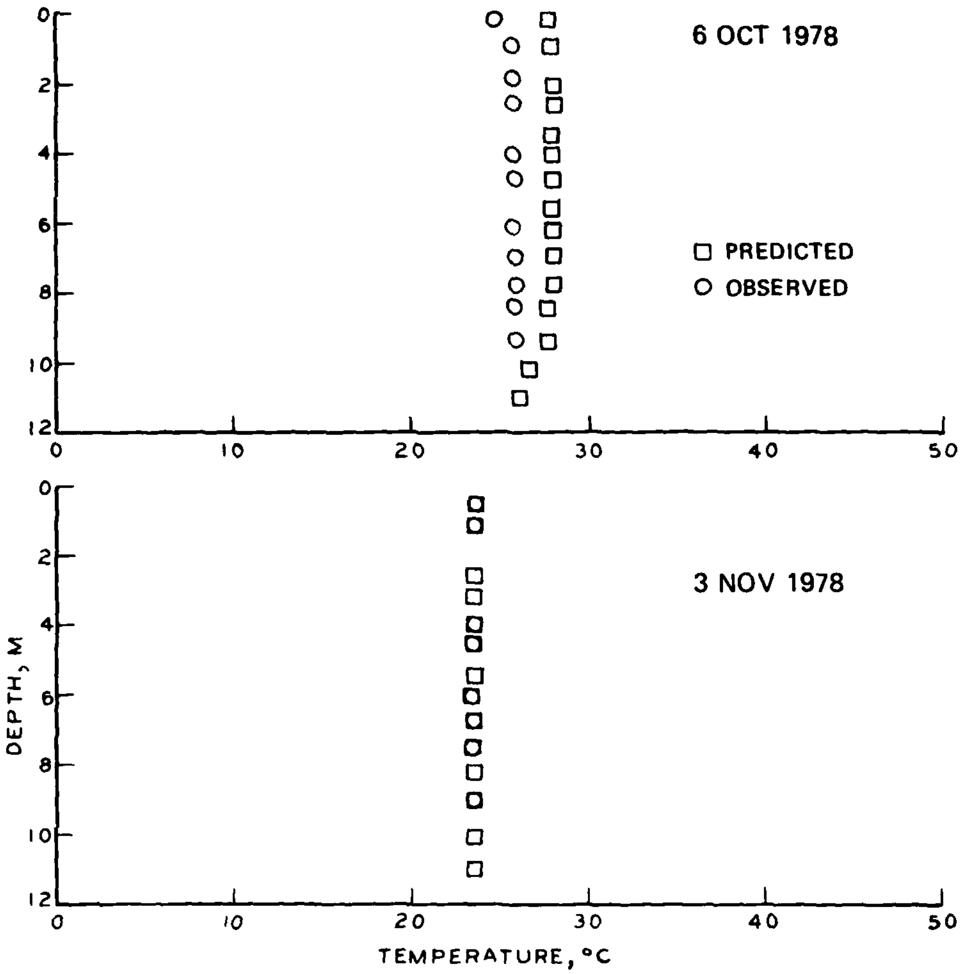


Figure 2. (Sheet 4 of 4)

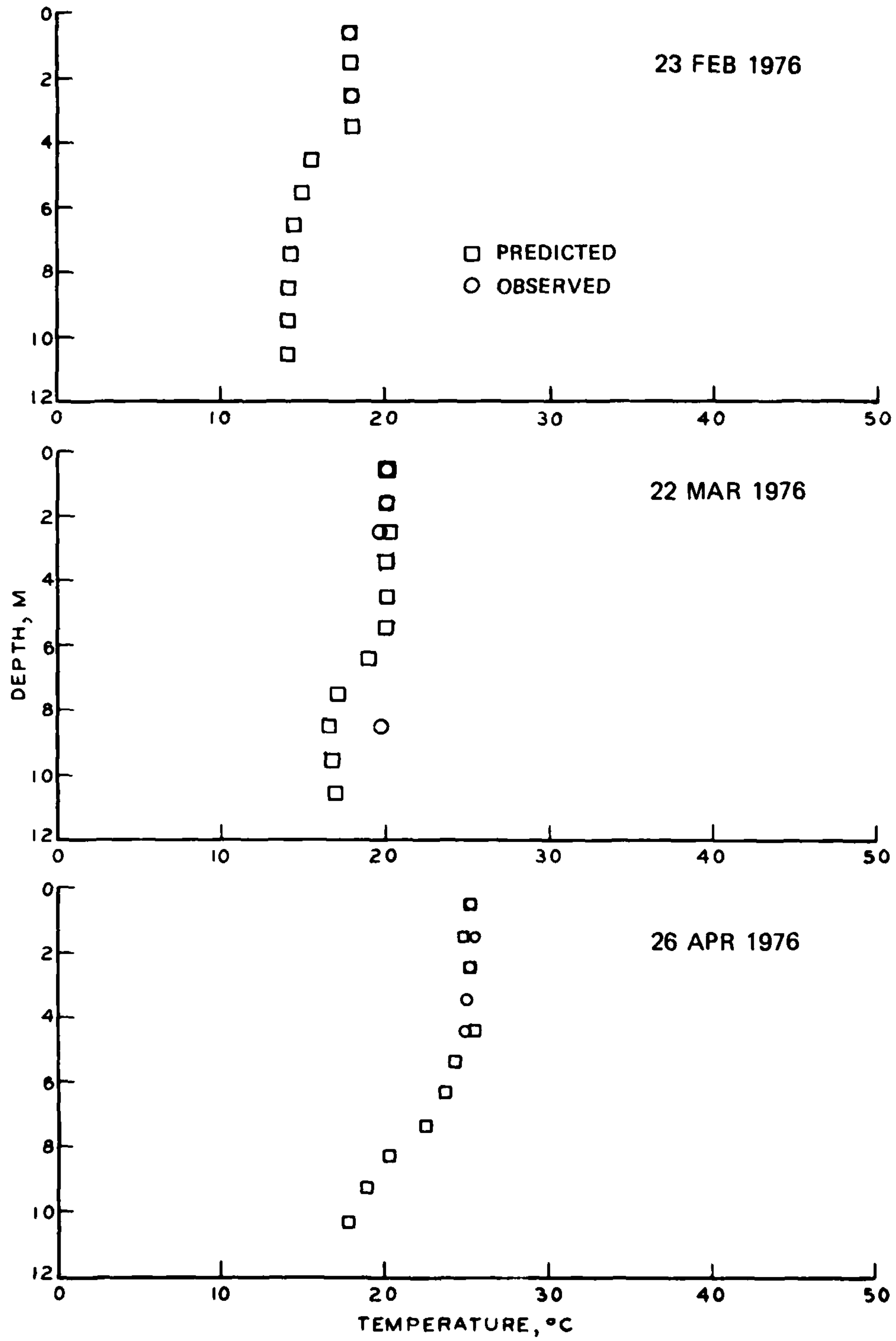
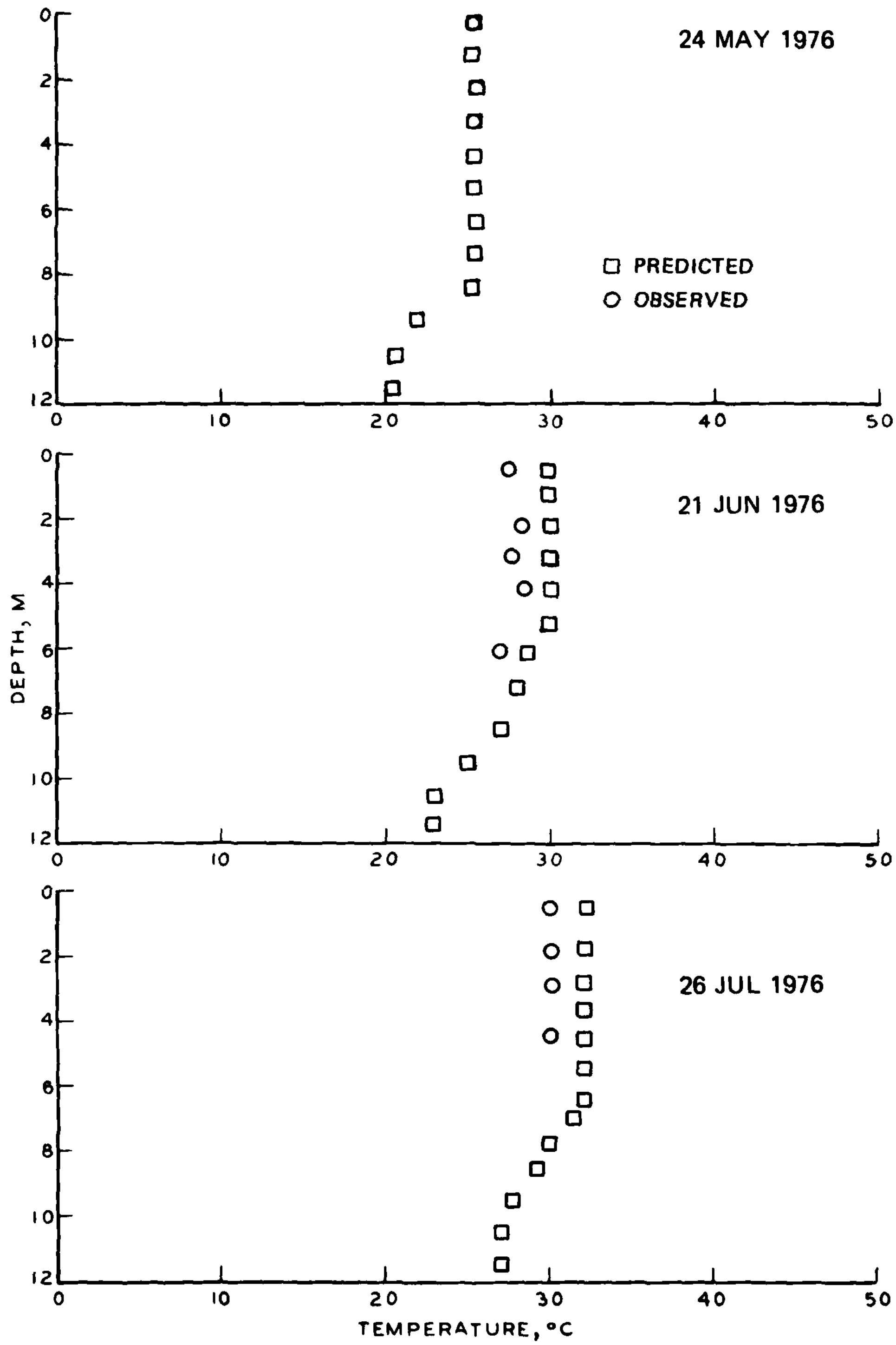


Figure 3. Temperature predictions from the verification simulations of the thermal portion of CE-QUAL-R1 (Sheet 1 of 11)



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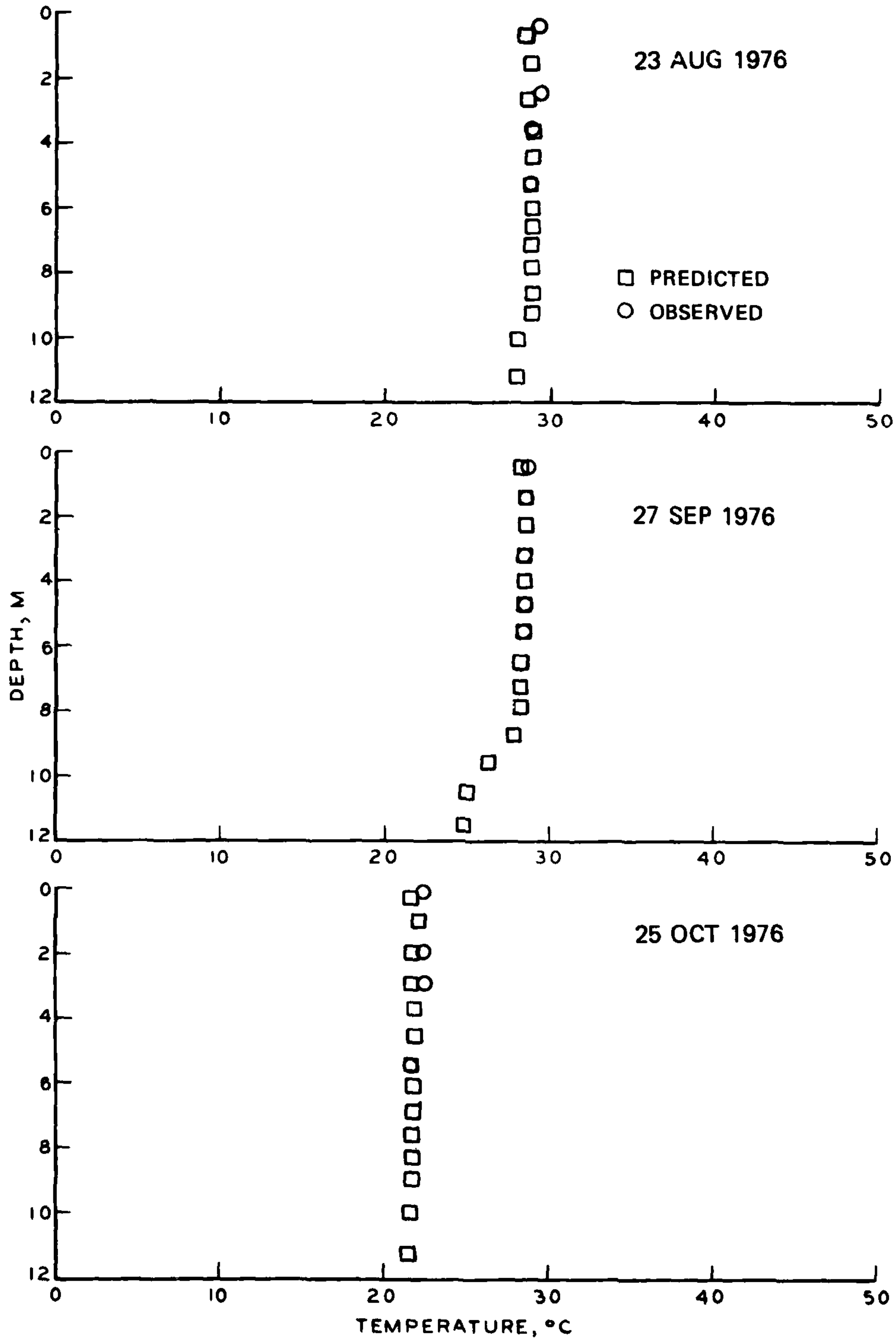

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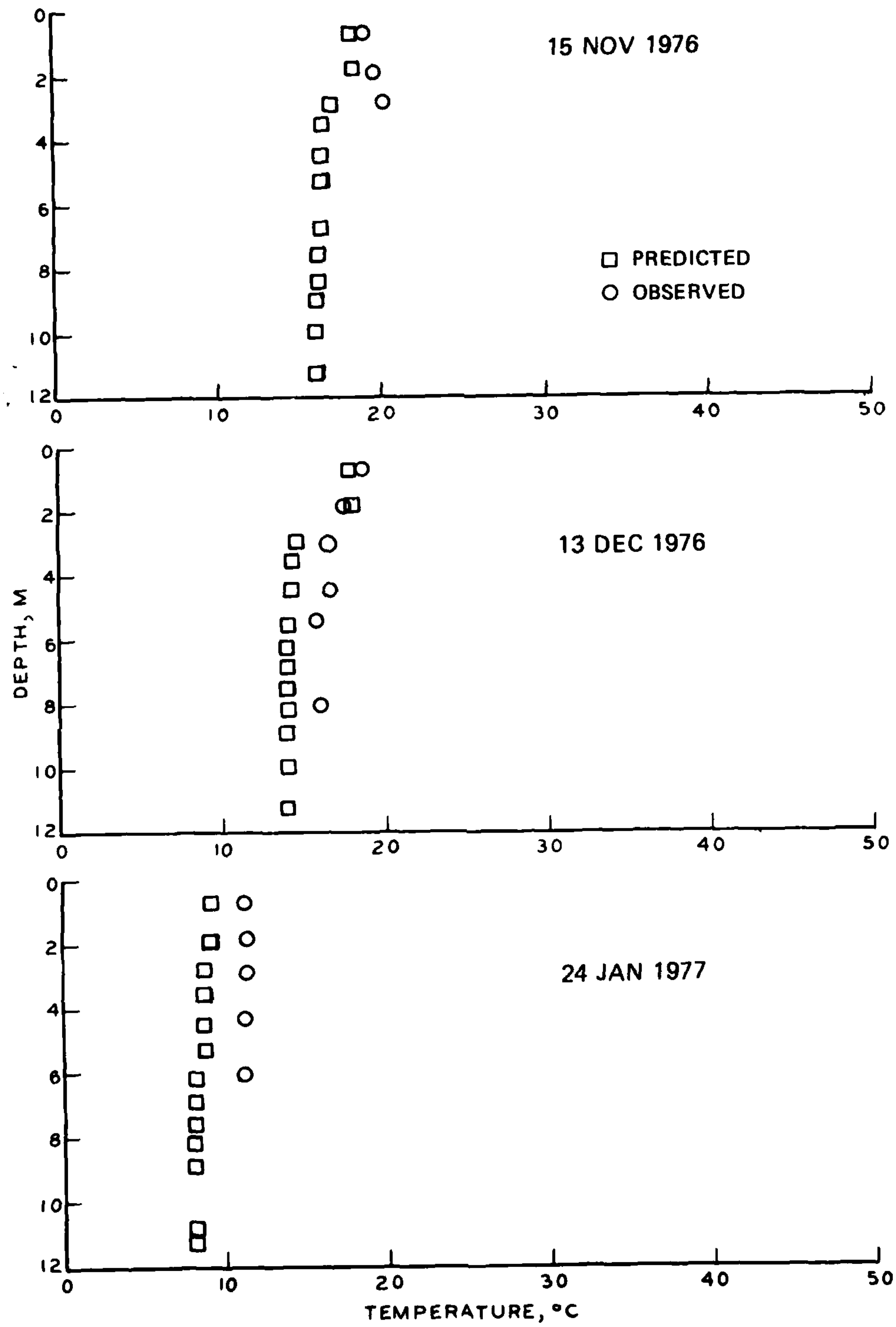
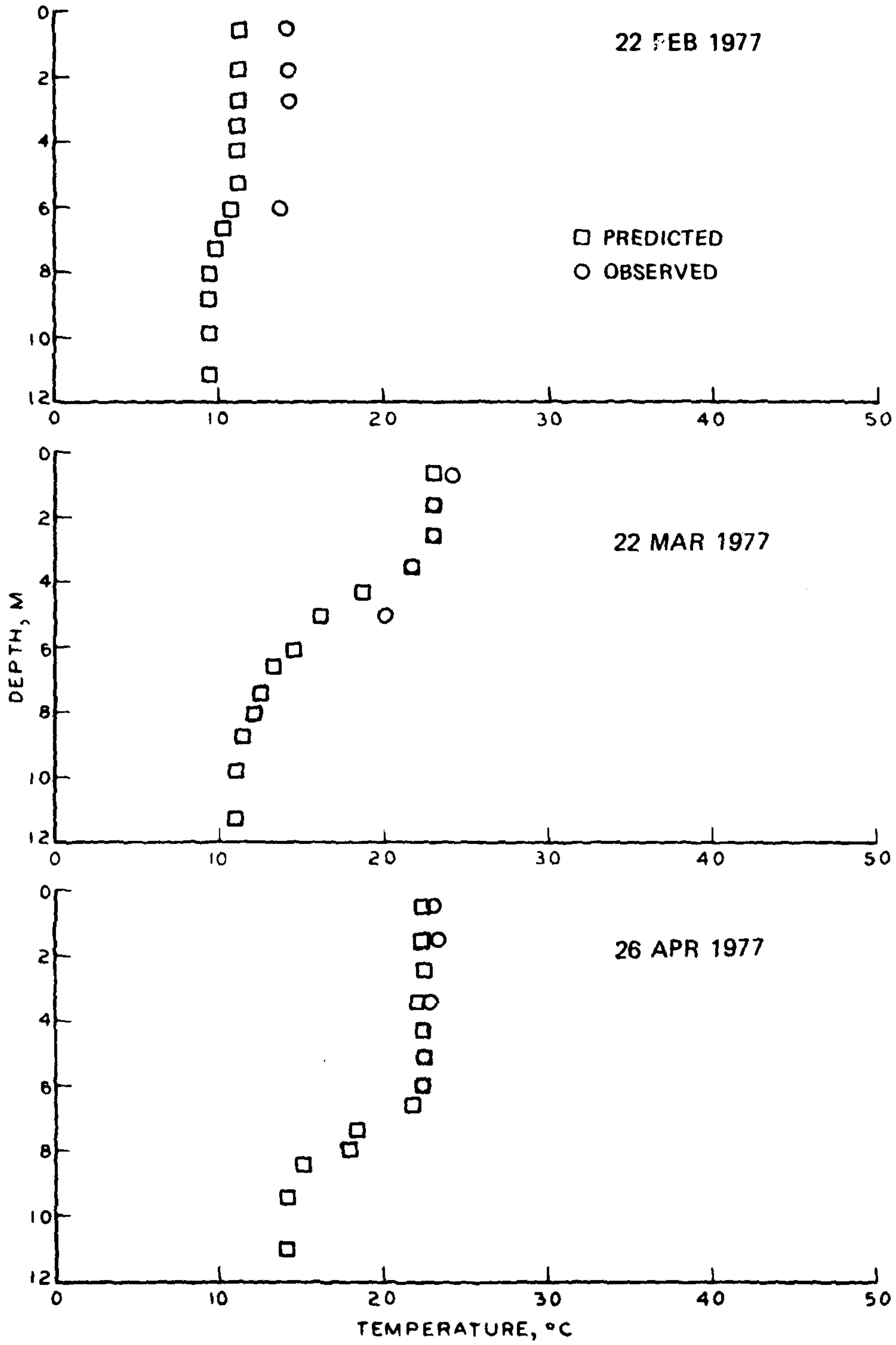


Figure 3. (Sheet 4 of 11)



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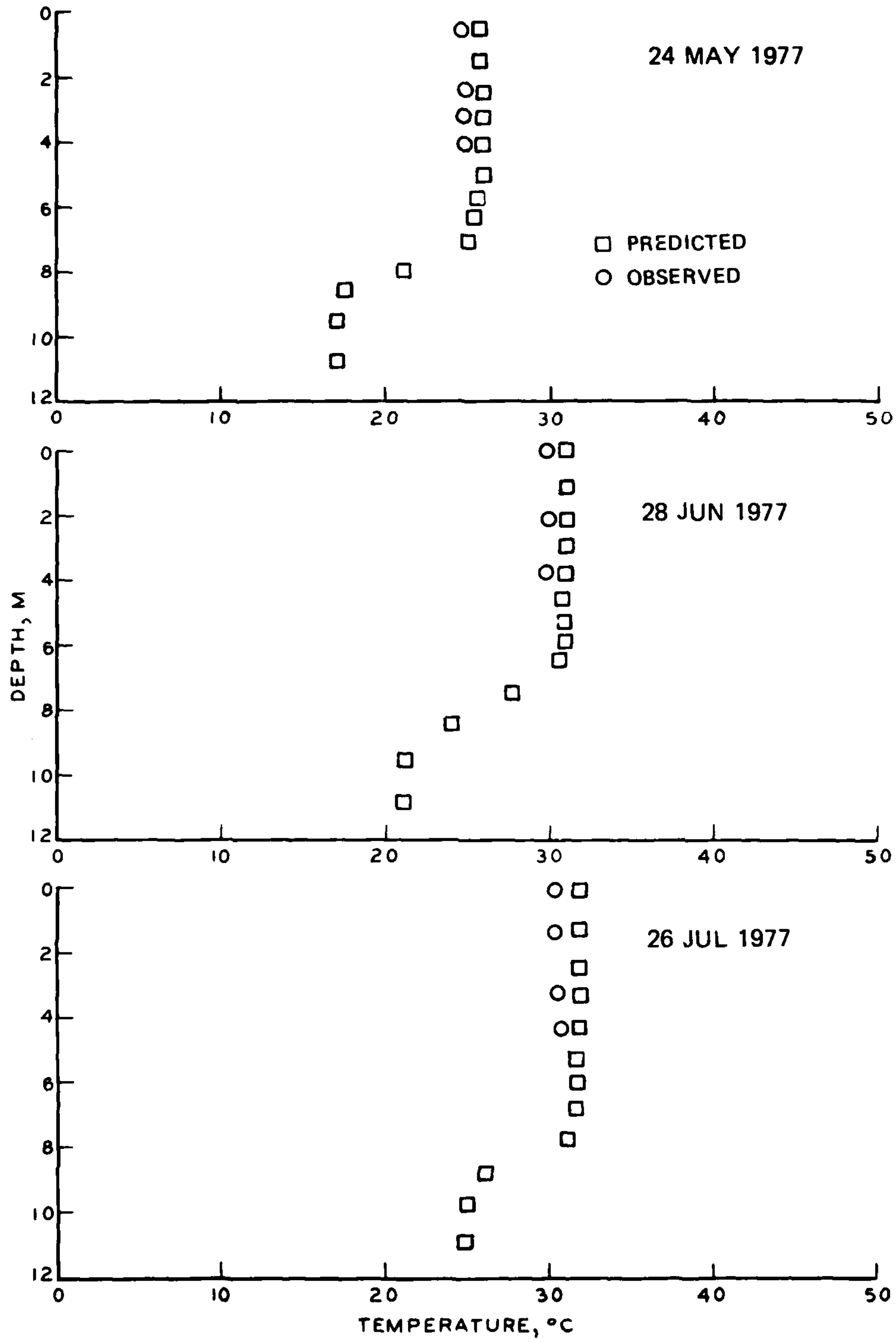

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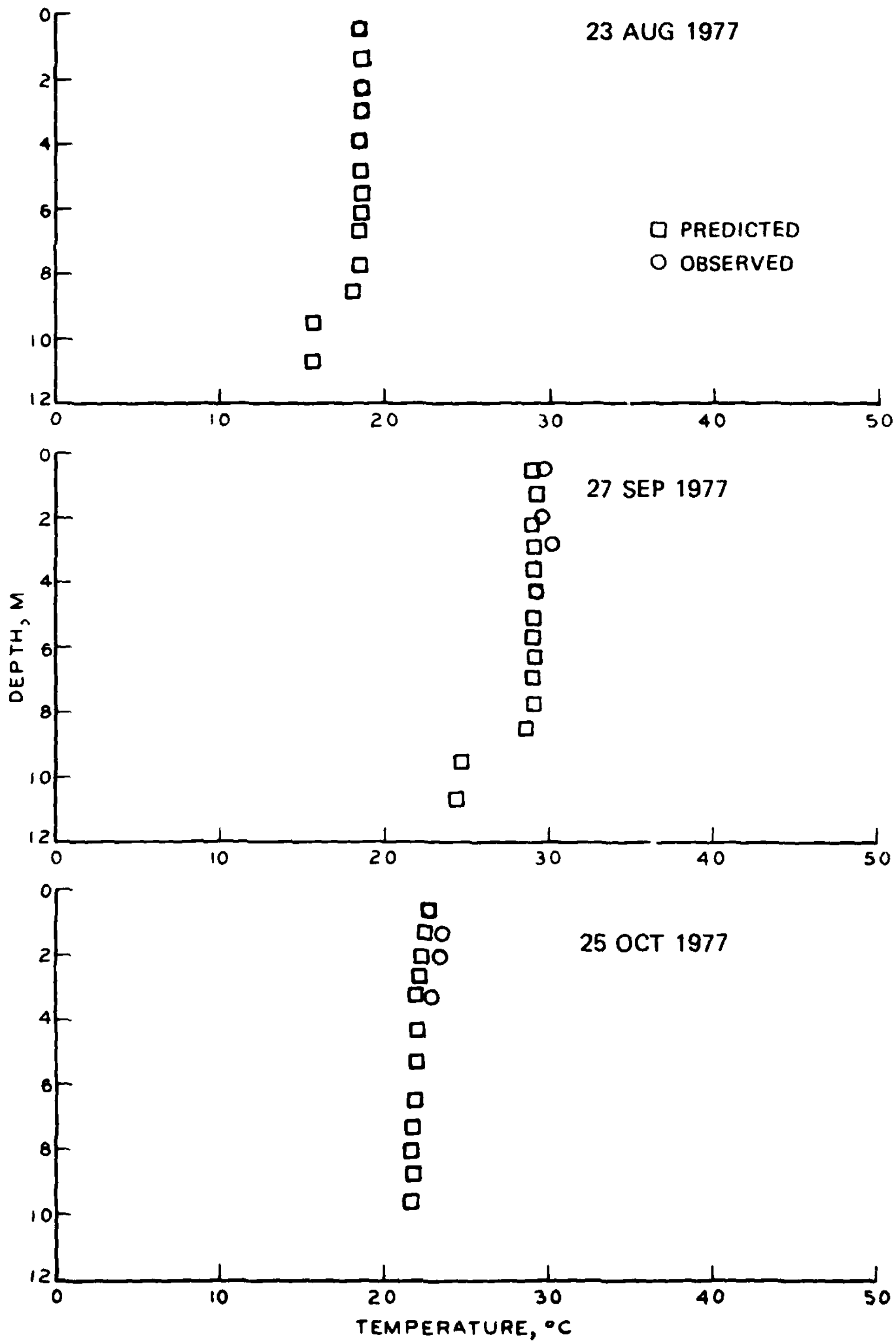

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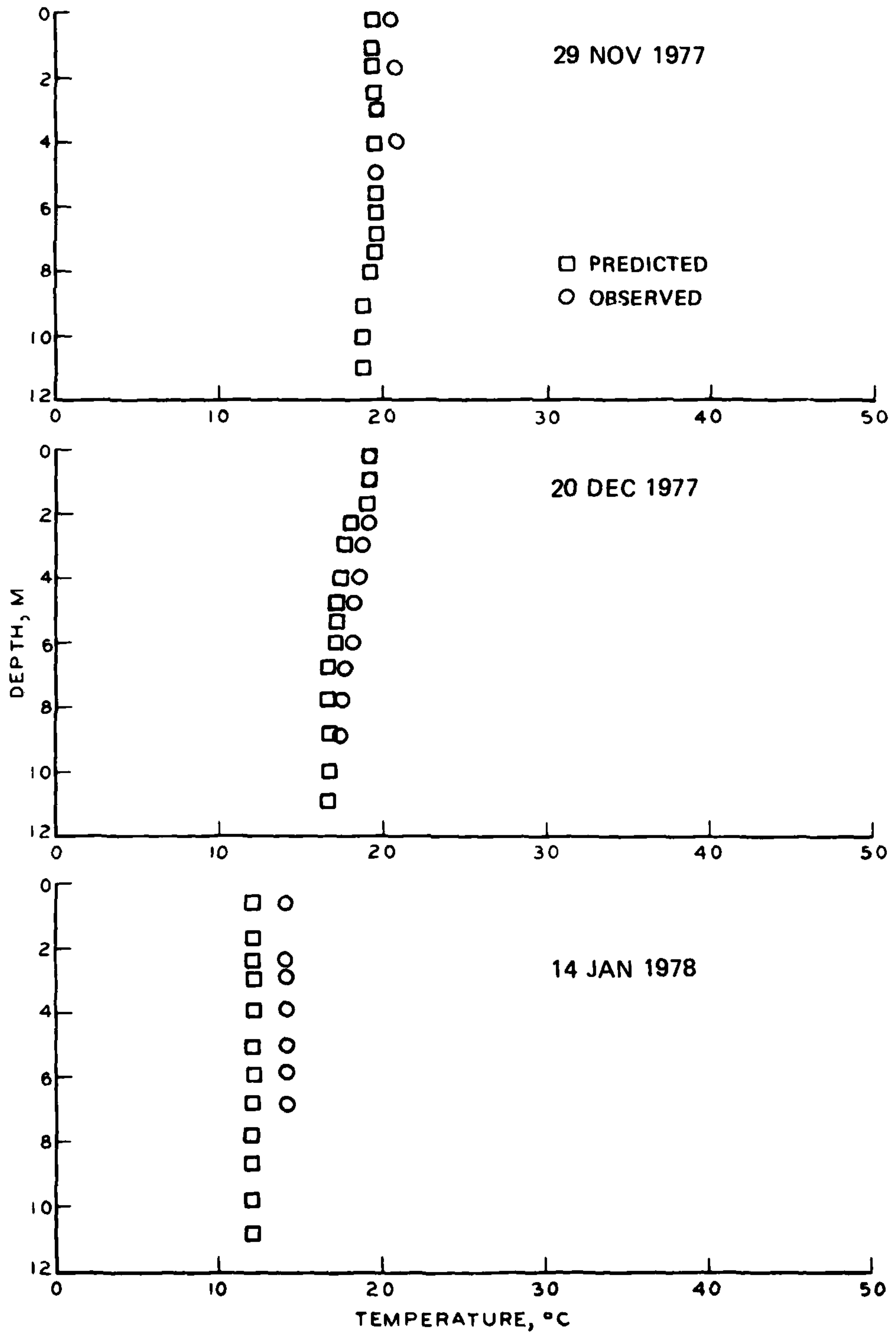

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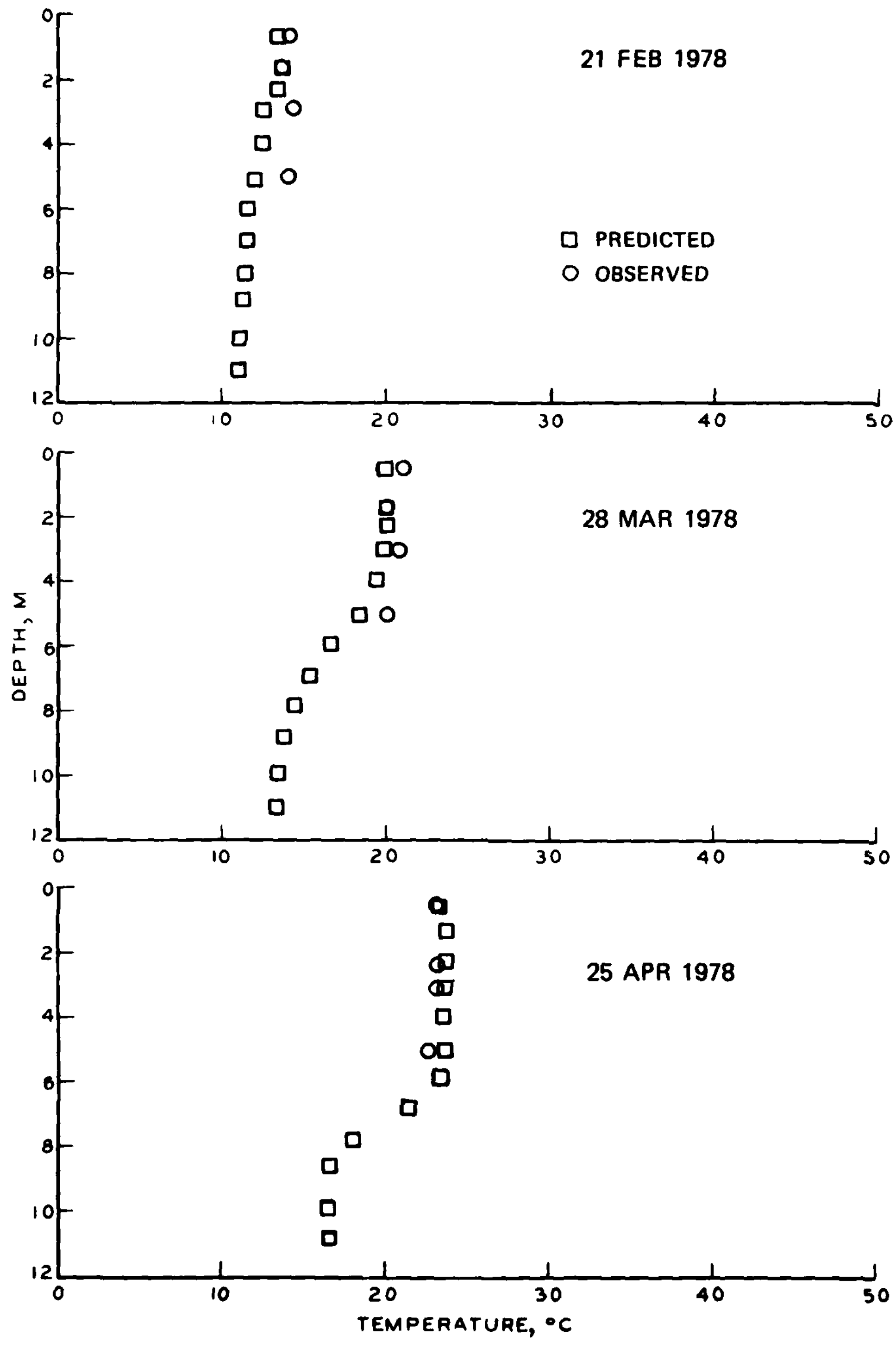

Figure 3. (Sheet 9 of 11)

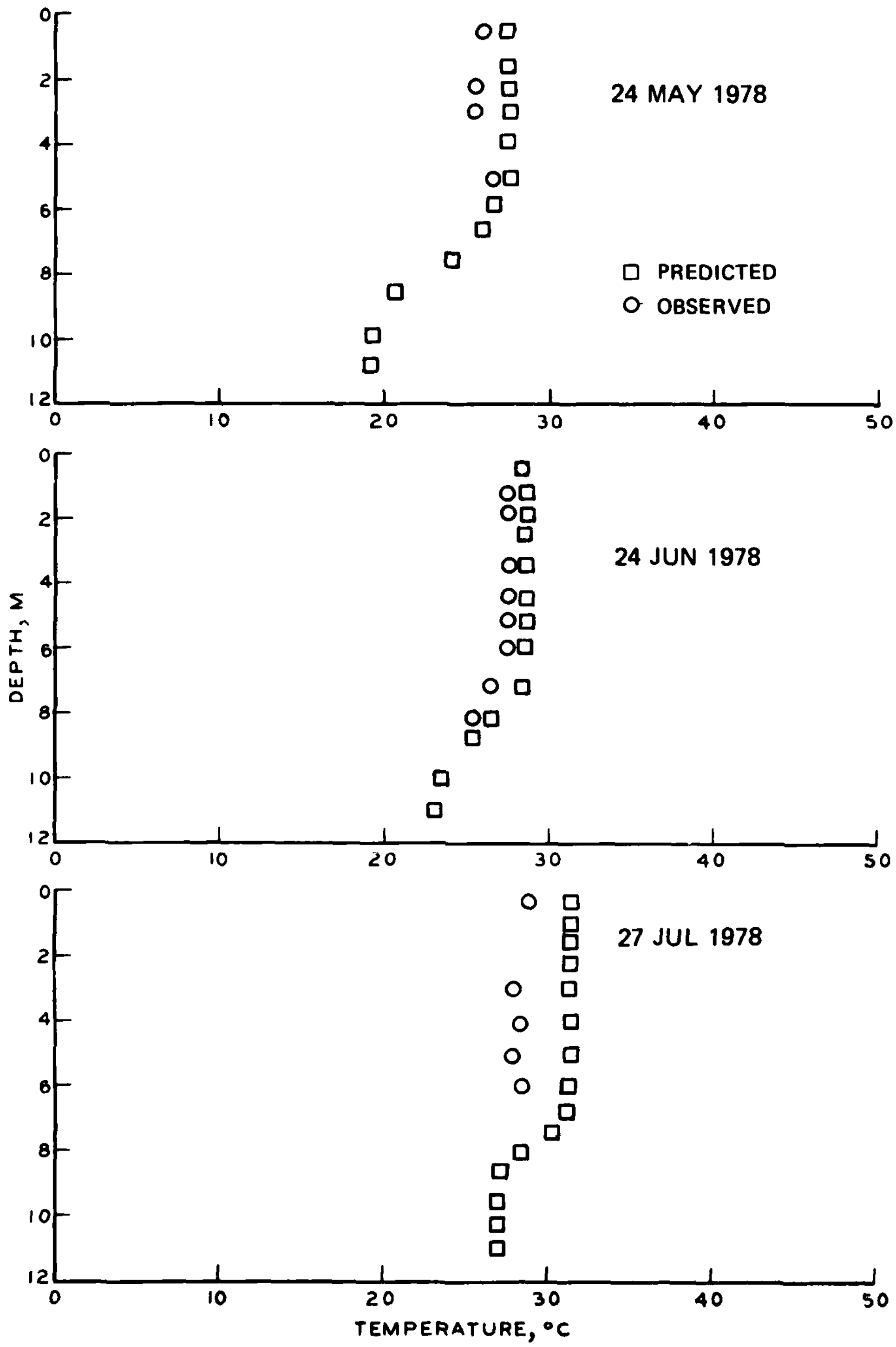

Figure 3. (Sheet 10 of 11)

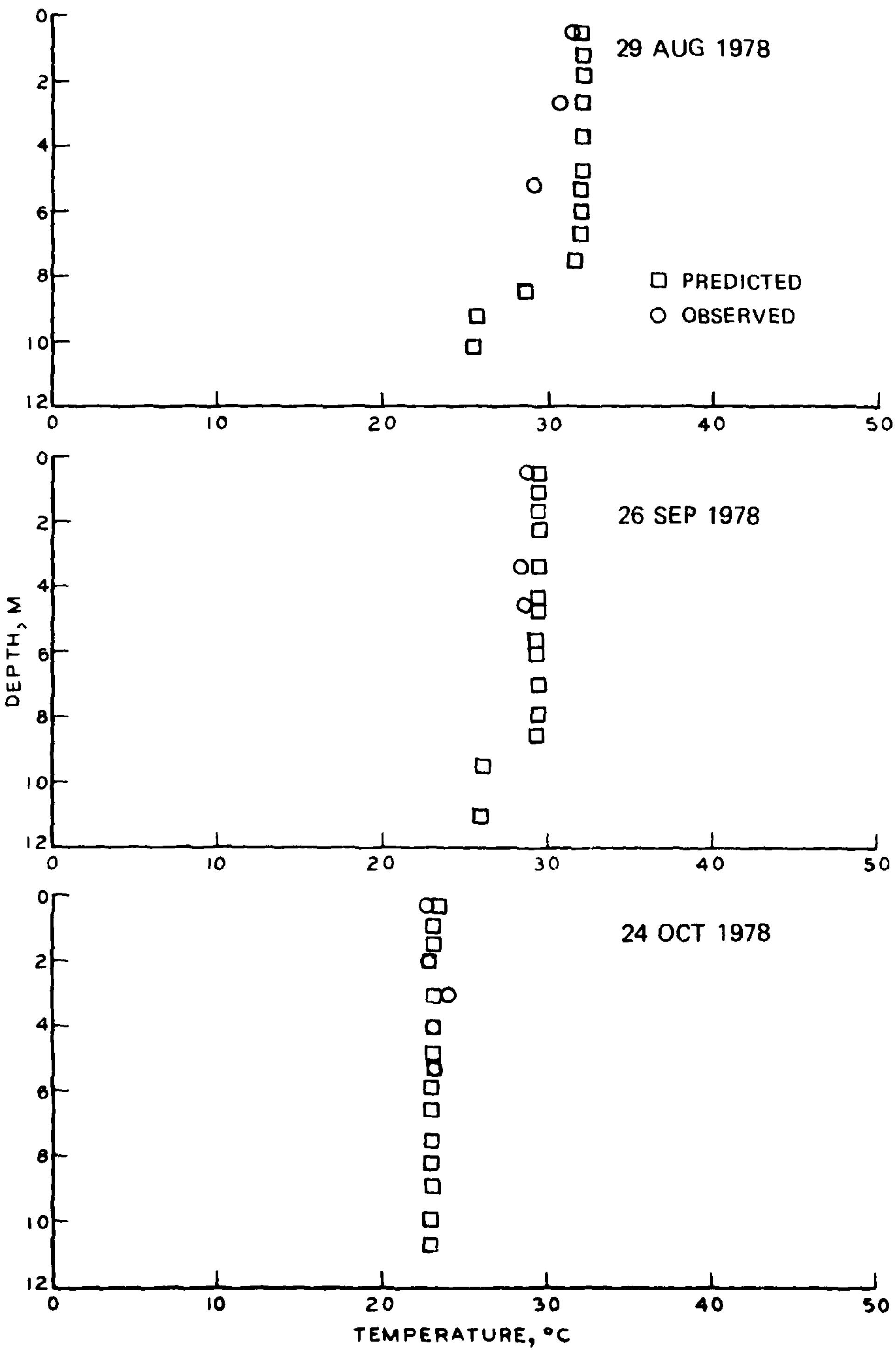

Figure 3. (Sheet 11 of 11)

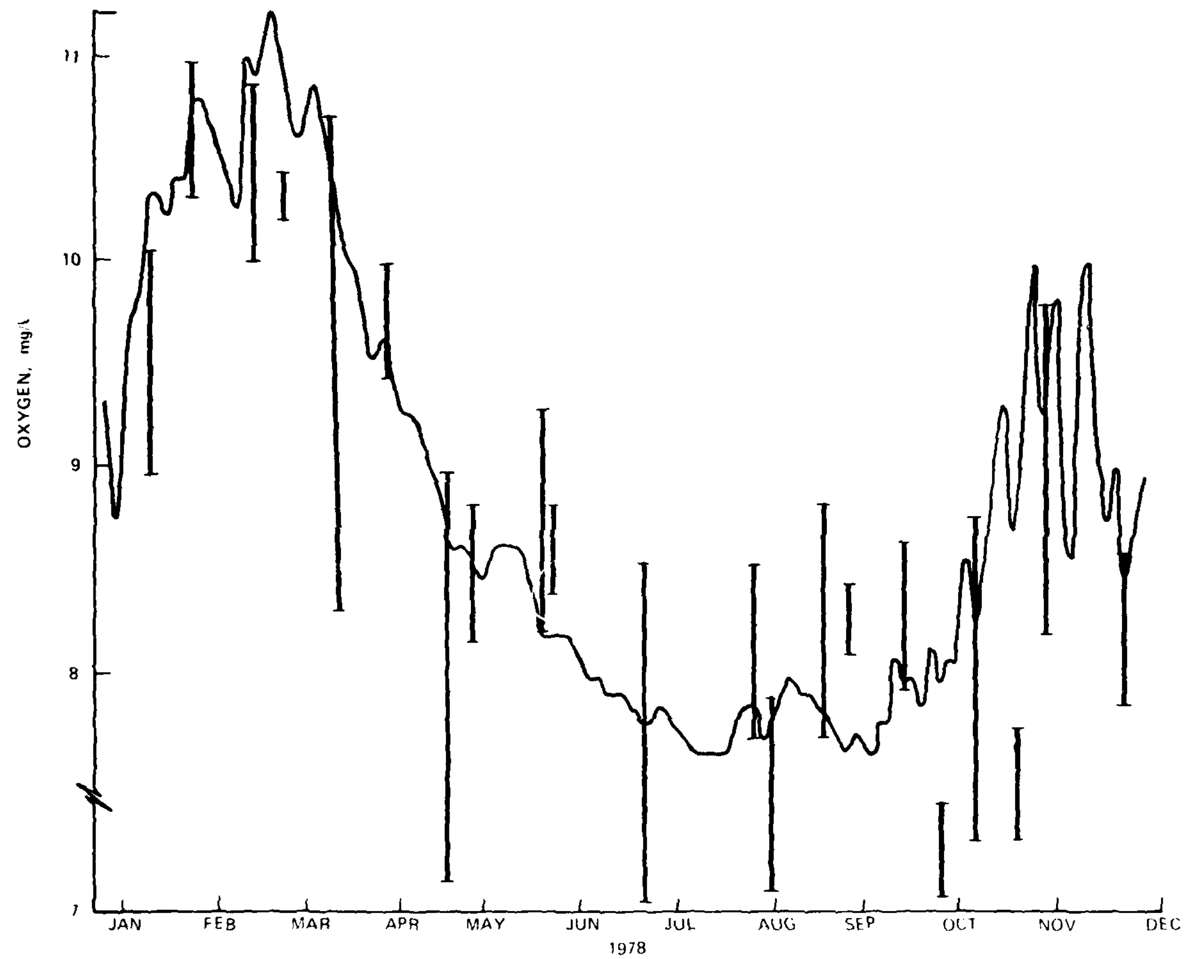

Figure 4. Simulation of oxygen in the surface layer. Vertical bars represent minimum and maximum measured values

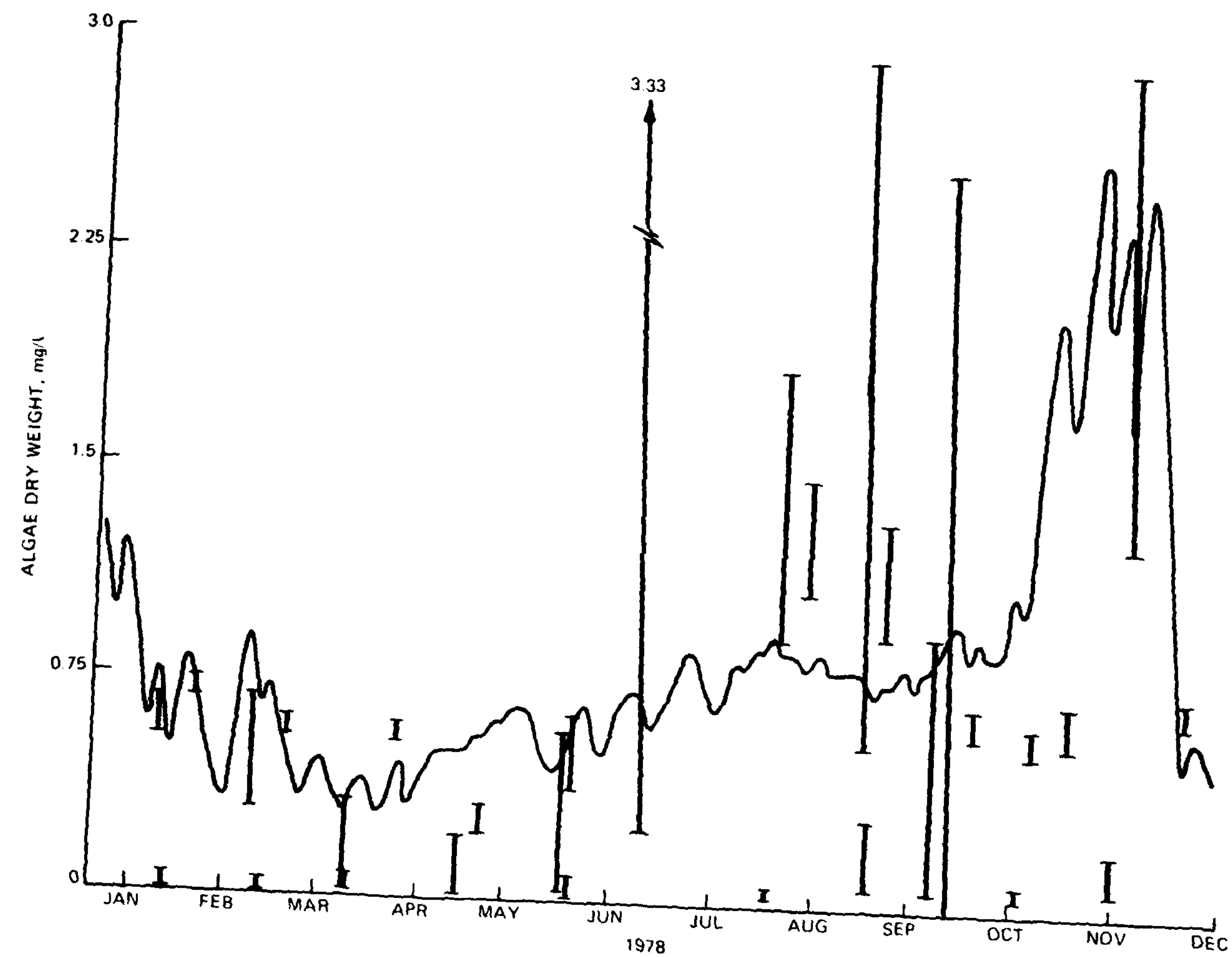

Figure 5. Simulation of algae in the surface layer. Vertical bars represent minimum and maximum measured values

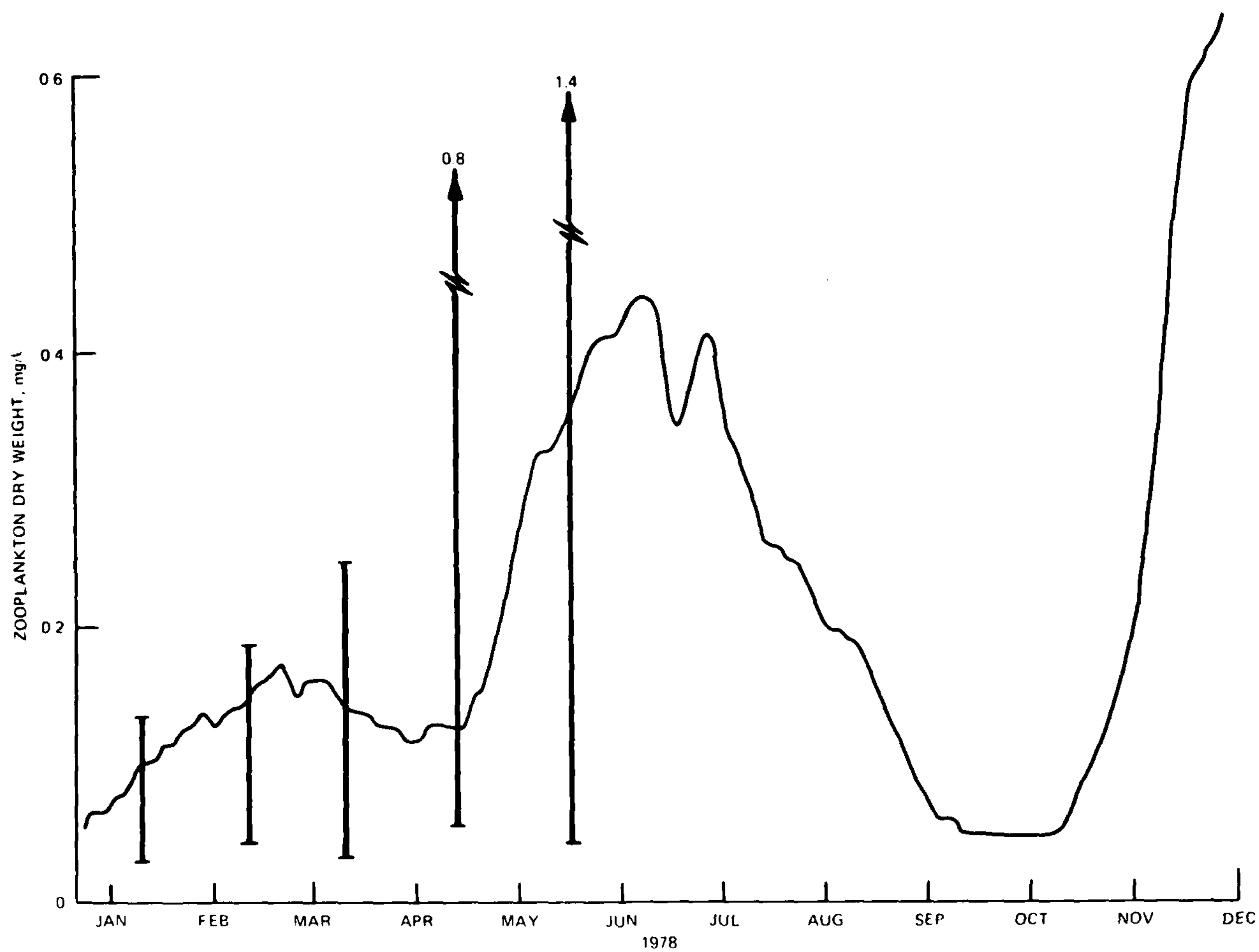

Figure 6. Simulation of zooplankton in the surface layer. Vertical bars represent minimum and maximum measured values

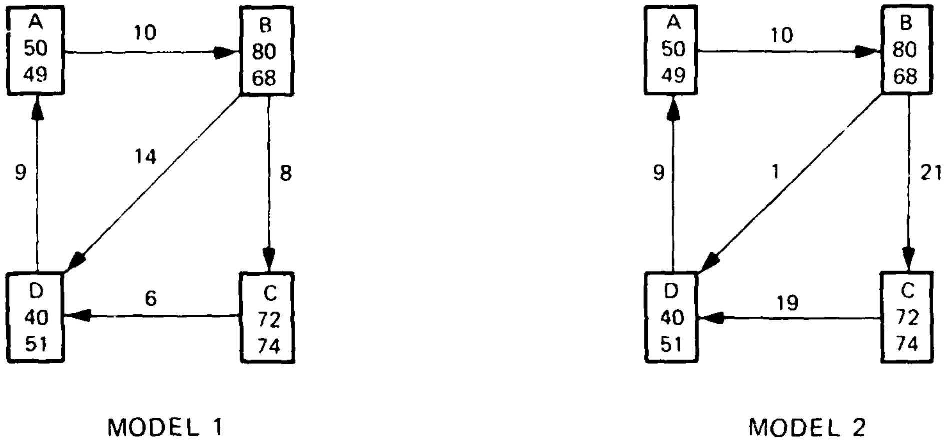

Figure 7. Two models with the same initial and predicted final values but with different rates of change

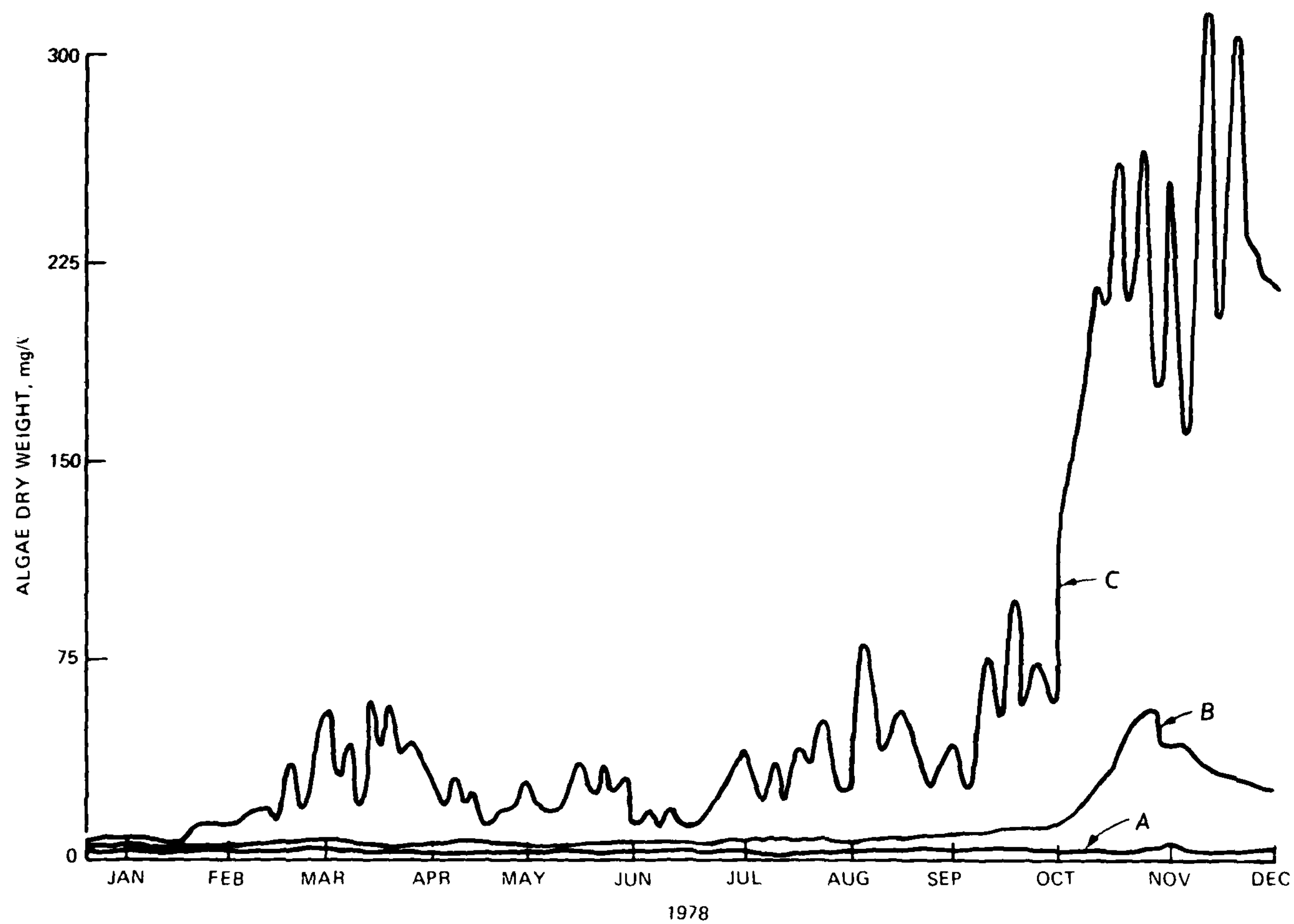

Figure 8. Simulation of algae in the surface layer. The three predictions are explained in paragraphs 50 and 51

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Wlosinski, Joseph H.
  Evaluation of the model CE-QUAL-R1 for use by the aquatic plant control research program / by Joseph H. Wlosinski (Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; 1981.
  27, [33] p. : ill. ; 27 cm. -- (Technical report / U.S. Army Engineer Waterways Experiment Station ; A-81-6)
  Cover title.
  "December 1981."
  "Prepared for Office, Chief of Engineers, U.S. Army."
  Bibliography: p. 26-27.

  1. Aquatic weeds. 2. Lake Conway (Fla.) 3. Mathematical models. 4. Reservoirs. 5. Water quality. I. United States. Army. Corps of Engineers. Office of the Chief of Engineers. II. U.S. Army Engineer Waterways Experiment Station. Environmental Laboratory. III. Title IV. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; A-81-6.
TA7.W34 no.A-81-6

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